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# STRATEGIES FOR TRANSPORTATION ELECTRIC FUEL IMPLEMENTATION IN CALIFORNIA: OVERCOMING BATTERY FIRST-COST HURDLES

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## Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Transportation

*The Strategies for Transportation Electric Fuel Implementation In California: Overcoming Battery First-Cost Hurdles* is a final report for the Potential Benefits of Transportation Electric Fuel Implementation in California project (Contract Number BOA-99-191-P). The information from this project contributes to PIER's Transportation Program.

For more information about the PIER Program, please visit the Energy Commission's website at [www.energy.ca.gov/research/](http://www.energy.ca.gov/research/) or contact the Energy Commission at 916 654 4878.



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## Abstract

Advances in electric-drive technology, including lithium-ion batteries, as well as the development of strong policy drivers such as California's Global Warming Solutions Act, now contribute to a more promising market environment for the widespread introduction of plug-in vehicles in California. Nevertheless, battery costs remain high.

This study discusses strategies for overcoming the significant hurdle to electric transportation fuel use presented by high battery costs. Generally speaking, strategies discussed include: reducing battery costs, finding appropriate markets and consumers, addressing various forms of cost financing, and offsetting initial costs with secondary-use applications—including an analysis of the net-present value (the long-term investment return value) of post-vehicle stationary battery use and its possible effect on battery lease payments.

Focusing on plug-in hybrids with minimized battery size, even the subset of values explored here (regulation, peak power, arbitrage, and some carbon-reduction credit) promise to lower plug-in-hybrid battery lease payments while simultaneously allowing vehicle battery upgrades and profitable repurposing of vehicle batteries for stationary use as grid-support, electrical storage/generation devices. Such stationary, post-vehicle “battery-to-grid” or B2G devices could not only provide valuable services needed by existing statewide grid-support markets, but could provide customer-side-of-the meter benefits, improve utility operation, help defer costly grid upgrades, and support the profitability and penetration of wind power and other carbon-reduction measures.

This study will benefit California ratepayers by increasing the use of alternative fuels, reducing criteria pollutants, and reducing greenhouse gas emissions.

**Keywords:** Electric fuel, plug-in hybrid, battery leasing, secondary use, ancillary services, grid storage, electric-drive-vehicle commercialization



# Executive Summary

## **Background**

Electric-fuel vehicles are experiencing a renaissance, based on several factors, including:

- Improvements in power electronics, electric motors, and advanced batteries (particularly lithium-ion).
- Policy drivers (in addition to California's longstanding and evolving Zero Emission Vehicle "mandate," these include the Global Warming Solutions Act of 2006 [Assembly Bill 32, Nuñez, Chapter 488, Statutes of 2006] and the "Pavley Law" for vehicle greenhouse-gas reduction [Assembly Bill 1493, Pavley, Chapter 200, Statutes of 2002]).
- Increased consumer awareness and demand, spurred by high and volatile gasoline prices, national security/geopolitics, global warming, and other concerns.

However, even with recent gains, battery costs remain high, and commercialization efforts face additional hurdles based on public acceptance of and demand for the unique attributes of electric-drive vehicles. In addition to the battery-electric vehicles of the past, additional viable designs have emerged based on plug-in hybrid architectures that attempt to capture some of the benefits of electric drive without all of the disadvantages of pure battery power. Even plug-in hybrids, with smaller battery packs than all-electric vehicles, face considerable cost challenges and uncertain consumer acceptance and adoption.

Plug-In Hybrid Electric Vehicles (PHEVs) are a near-term automotive technology that offers a transition strategy to increase the use of electricity in transportation so as to displace fossil fuel use and reduce greenhouse gases from the transport sector. PHEV designs can use a variety of drive-trains and control strategies to create a "dual-fueled" vehicle that can be powered serially or simultaneously by liquid fuels or electricity from the grid, stored in batteries. PHEVs differ from regular hybrid electric vehicles (HEVs), primarily in that they can recharge their batteries from "plugging into" grid connections and have much larger batteries.

## **Battery Size**

Though large-battery plug-in vehicles would likely provide greater emissions and energy-dependence reductions, spurring commercialization through policy support of lower-cost, lower-barrier technologies—for example, small-battery, blended-mode plug-in hybrids with shortened battery deployment—may lead to easier and quicker adoption of electric-fuel technologies. Not dependent on recharging, and thus able to use a sparser, cheaper, and less coordinated recharging infrastructure without significant compromise, plug-in hybrids face nontrivial but significantly lower infrastructure barriers while simultaneously benefiting from advances in the existing engine and fuel industries. With initial adoption of these electric-fuel technologies, the accordant changes in marketing, consumer behavior, supply channels, and so forth may ease larger-scale shifts to electric-fuel implementation over time.

Additionally, policies that support road-load reductions (improved lightweighting, aerodynamics, and rolling) produce efficient vehicle platforms, thereby reducing the power, energy, size, and cost of the batteries and other electric-fuel technologies required.

## ***Production Volume and Markets***

Per-unit battery costs can be reduced through materials and process improvements and by spreading costs over a larger volume of production. Production volume can be increased by targeting high-volume applications and through standardization of battery cells or modules for use across multiple applications. Automakers and suppliers are pursuing strategies to expand the production volume of electric-drive technologies through supply to various partners and otherwise competitors, even to the extent of one automaker producing vehicles to be branded and sold by another.

Previous studies find that one-third, possibly up to one-half, of Californians appear pre-adapted to early plug-in vehicle adoption or otherwise *able* to use plug-in vehicles. They represent the maximum, though not immutable, *initial market potential*, from which light-duty plug-in vehicle sales will likely be drawn, forming the buydown base for the incremental costs of the required innovations.

Beyond this private-vehicle market segment, various opportunities exist for supporting commercialization in organizational fleets. Because fleets have long been thought of as a promising mechanism by which alternative-fuel vehicles might somehow gain a foothold and increase volume, while significant overall progress in alternative-fuel vehicle commercialization remains elusive, a discussion of the suitability of using fleets as plug-in-vehicle niches is presented using several high-tech strategic marketing principles of particular relevance to electric-fuel commercialization. These marketing principles are expanded in a discussion of early adopters and consumer willingness/ability to pay. Collectively, this discussion relates how to better support the dynamics of electric-fuel innovation and commercialization.

## ***Financing Mechanisms***

Consumers pay for cars and their use in various ways, each presenting a leverage point for policies hoping to support electric-fuel use. Tax credits, grants, feebates (that is, revenue- and potentially vehicle-size-neutral rebates on efficient vehicles coupled with fees on inefficient ones), and non-monetary benefits such as carpool and parking privileges are all policies in active use that can be targeted to encourage electric-fuel use and ameliorate battery first cost hurdles. Further, various creative financial frameworks could help consumers pay for plug-in vehicles. One example goes beyond the net-present-value of life cycle cash flows and uses a “real options” framework that values future streams of fuel choice options provided by plug-in hybrids, which, if accounted for and incorporated into new business models, reportedly raises the break-even battery price approximately \$100 per kilowatt-hour (kWh). In another illustrative example, [4] municipalities are developing financing to pay for home solar installations to be repaid by the homeowner via property tax assessments, thereby dramatically reducing consumer upfront cost and credit implications and transferring the debt to low-rate equity / mortgage financing. Such systems could be adapted directly or analogously to help finance home electrical service upgrades and recharging facilities, if not battery and plug-in vehicle technologies.

## ***Battery Leasing***

Battery leasing is a potentially powerful mechanism that could allow plug-ins to compete on a favorable basis, shifting the terms of the business case from upfront, capital costs to life cycle

costs. It could give battery suppliers a profit-margin incentive to develop long-lasting, recyclable batteries and drivers peace of mind, consistent “fuel” charges, and the incentive to maximize zero-tailpipe-emission, efficient electric-fuel use. A leased battery also need not last the life of the car, but could be periodically replaced without disrupting the service contract with the consumer, for example, during routine maintenance at increasingly longer intervals as the technology matures. Depending on the business model, challenges include multiple-party coordination for product development, standardization, marketing, sales, and service/warranty. Additional challenges stem from (among other sources) variable use by different customers with different use and charging patterns, and multiple battery chemistries and requirements.

One apparently successful example of battery leasing is Modec UK ([modeczev.com](http://modeczev.com)) and its partnership with GE Capital to supply custom battery-EV urban commercial delivery trucks with, for example, four-year battery leases. Another highly publicized and aggressive start-up example, Better Place, aims to go beyond leasing both batteries and home recharging on a per-mile basis to include access to away-from-home opportunity charging and battery switching stations, all for battery-only electric vehicles. The latter are capital-intensive, network/subscription business-model “plays” and are not necessary for plug-in hybrids.

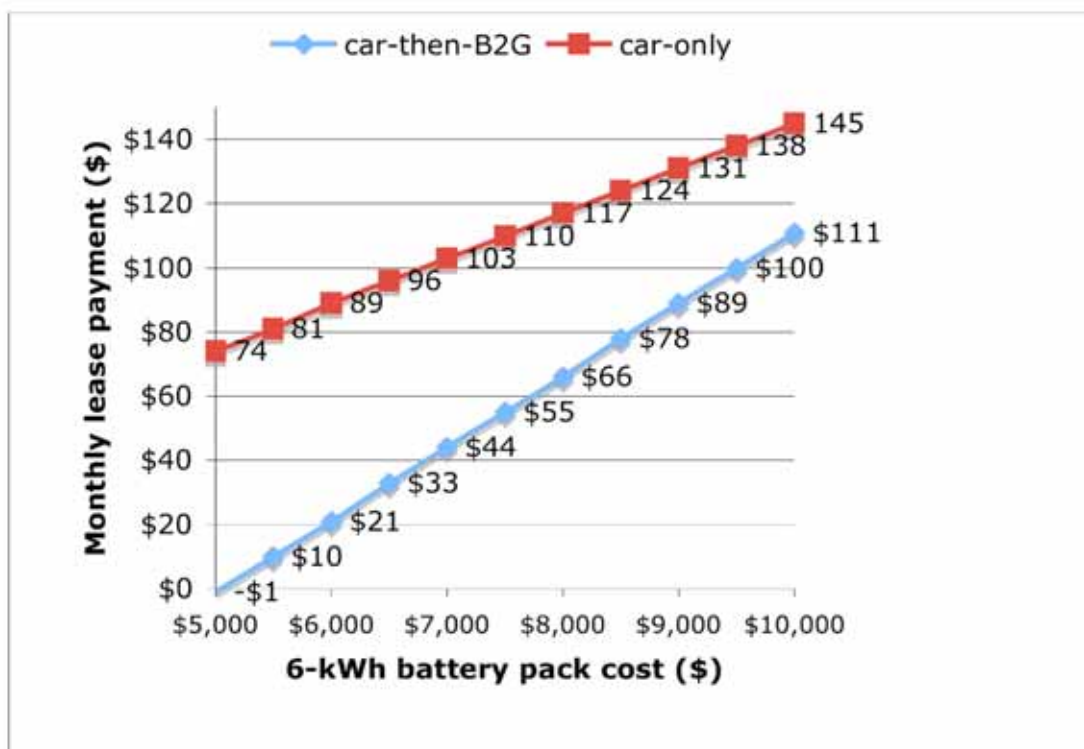
### ***A Strategy for the Electric-Fuel Transition***

Working in concert, several strategies discussed in this section could be employed to alter the early commercialization picture for electric-fuel vehicles in California. Like the vehicles they help, these strategies straddle automotive and electrical-energy worlds, embracing their convergence. They include: battery downsizing, standardization, and leasing, with shortened initial vehicle deployment and repurposing/down-cycling into stationary use for building and grid-support services.

The authors show that strategies based on minimizing the battery size and cost through reducing the time period in which a battery is expected to be used in a vehicle, combined with strategies for capturing later-stage battery value in stationary applications, can help to reduce the estimated initial lease prices of new plug-in vehicle batteries. Focusing on small-battery, blended-mode plug-in hybrids and assuming high initial battery costs, even the subset of values explored here (regulation, peak power, arbitrage, and some carbon reduction credit) promises to lower battery lease payments while simultaneously allowing vehicle battery upgrades and profitable repurposing of vehicle batteries for stationary use as grid support, electrical storage and generation devices. Such post-vehicle, stationary “battery-to-grid” devices could not only provide valuable services needed by existing statewide grid-support markets, but could provide customer-side-of-the meter benefits, offer demand-response services, improve utility operation, help defer costly grid upgrades, and support the profitability and penetration of wind power and other carbon-reduction measures.

Third-party or other non-conventional ownership arrangements and battery leasing might not only align incentives for battery improvements and full and responsible use, but may allow the net-present-value of these and other battery services to be accounted for in the initial vehicle transaction, lowering costs, and easing initial design and commercialization expectations. Using the case analyzed in subsection 2.6 as an example shows that, if such “residual value” for a mid-sized plug-in-hybrid battery could be brought into the lease calculation, a \$131-per-month, car-

only lease requiring full depreciation over 10 years is lowered to a \$90-per-month, five-year lease in the repurposing scenario. This offers both monthly savings in addition to the opportunity to upgrade the vehicle's electric-drive performance every five years with a newer, presumably cheaper and more capacious/powerful pack. Further, several types of potential benefit have not yet been quantified (for example, subsection 2.6.8) and could greatly improve these already intriguing prospects.



**Figure 1. This illustrates the sensitivity of the lease payment to initial battery pack costs, adjusted for the subset of post-vehicle, secondary “residual” value.**

Of course, the full realization of benefits is predicated upon several assumptions and pre-conditions, requiring coordination, standardization, and granting battery-to-grid units access to several existing and future markets. Initial policy steps already identified that would allow or improve the strategies like those described here include modifying certifying procedures to include battery storage devices as California Independent Systems Operator (California ISO) generating units, further rewarding fast-response units in proportion to their operational and other benefits, and providing investment incentives.

Additionally, further analysis should weigh the benefits of implementing household/building battery-to-grid (in both the current context and the context of the coming “smart grid” wherein household device control may be implemented for other reasons anyway) vs. spatially combining battery-to-grid units into “battery-pack power plants” or demand-response units, which should have economies of capital, operational, and transactional scale and simplify certain challenges.

Given the many potential benefits to the grid, third-party ownership and/or rate-based utility investment in such batteries may be justified or even encouraged by state and national policy (subsection 2.7)—strengthening ever-tightening connections between transportation and stationary energy and helping to launch a new era of electric-fuel technologies. Estimation of the full range of ratepayer benefits from utility involvement in electric-fuel vehicles will be important to the further development of this concept, but initial evaluation indicates ratepayer benefit could be considerable, through higher off-peak grid usage, greater acceptance of intermittent renewables, and additional grid-support services. To meet its various challenging policy goals (for example, carbon reduction), California could leverage these grid-storage benefits to help launch electric-fuel-vehicle implementation.

As battery costs are expected to fall over time, efforts should focus on reducing barriers to adoption in the near term to establish markets, supply chains, and infrastructure, and to build production volumes. Battery lease models offer one mechanism for helping to establish a framework for capturing battery values throughout their life cycle. Private and public involvement, through battery leasing and the establishment of stationary applications for plug-in-vehicle batteries, in conjunction with other efforts to help provide recharging and electric power metering infrastructure, could be important to improving the likelihood of success of the current attempts to commercialize electric-fuel vehicles.

### ***Benefits to California***

This study provides information on economics and business models that, if implemented, would accelerate the use of electricity as a transportation fuel. Electrifying California's transportation modes, especially light duty vehicles, will result in decreased dependence on petroleum, decreased emissions of criteria pollutants and decreased production of greenhouse gasses.

The primary benefits to California of transitioning to electric fuels are the lessening of demand for imported and dwindling fossil fuels, as well as the lessening of CO<sub>2</sub> from the transport sector. The sizing and secondary use of electric vehicle batteries, the convenient provision of charging opportunities, the favorable pricing of electricity, the effective financing of batteries, will all contribute to an increased shift of transport energy to electricity, thus achieving the primary goals.

California's electricity system does not use petroleum. It also produces less CO<sub>2</sub> –equivalent emissions per energy unit than petroleum fuels due to its mixed use of natural gas, hydroelectric, renewable, and nuclear. California utilities will produce even fewer greenhouse gases in the future as they increase the percentage of renewable energy from biofuels, geothermal, wind, and solar. There are a variety of transportation technologies that already run on electricity including trolleys, subways, and light rail. However, light-duty vehicles produce the great bulk of transport emissions and therefore greenhouse gas emissions in California.

**Note:** All figures and table within this report were created for this report, unless otherwise noted.

# 1.0 Introduction

## 1.1. Background

The state of California has been attempting to encourage the commercialization of electric-fuel vehicles since the late 1980s, when the California Zero Emission Vehicle (ZEV) “mandate” was conceived. Led by the California Air Resources Board (ARB), this effort saw various fits and starts in the 1990s. There was no sustained progress as originally planned with the program that would have initially required 2 percent of vehicles offered for sale by major manufacturers to have been ZEVs starting in 1998, ramping to up 10 percent by 2003. This original ZEV mandate program would have required approximately 100,000 ZEVs to be introduced per year in California by 2003.

The ZEV program has evolved considerably since that time, now requiring many fewer ZEVs but significant numbers of other clean and efficient vehicles, including “advanced technology partial ZEVs” or “AT-PZEVs.” This vehicle category includes qualified hybrids that use electric motors to help reduce the use of gasoline and the production of air pollution and greenhouse gases.

Conditions today, in early 2009, are quite different than they were in the 1990s. As a result, the prospects for widespread introduction of electric-fuel vehicles are much more promising. Important differences include:







- California and other state and regional efforts to address the issue of climate change are dramatically further along than they were in the 1990s, particularly in California with the passage of AB 32, the “Global Warming Solutions Act” that requires California’s greenhouse gas (GHG) emissions be reduced to 1990 levels by 2020, and the Low Carbon Fuel Standard.
- Electric-drive technology has advanced in performance and reduced in cost, with much improvement in electric motors and power electronics, and with high-performance lithium-based batteries now on the cusp of volume production.
- The dramatic rise in crude oil and gasoline prices in 2008 has spurred a consumer shift toward more efficient vehicles.
- The United States automobile industry has fallen on hard times, with a faltering business model overly dependent on sales of the largest, heaviest, conventionally-powered passenger vehicles, and is now starting to recognize that it must innovate and focus on electric-drive technology in order to compete globally and survive in a highly competitive market environment.

Taken together, these developments provide a very different and more promising, though economically challenging, market environment for the widespread introduction of electric-drive vehicles (EDVs) and the “implementation of electric fuel” in California.

There are still considerable challenges, related to the high cost of advanced batteries and fluctuating oil and gasoline prices that provide an uncertain economic environment and uncertain consumer response to the new vehicle types. Even in the absence of vehicle cost, performance, and/or infrastructure limitations, robust private value propositions for electric-

fuel vehicles are needed to spark and sustain their widespread commercialization and to displace entrenched gasoline and diesel-powered cars and trucks. The authors suggest that EDVs will very likely not sell widely simply as clean cars and trucks; they must also be marketed as new products that provide innovative value to consumers. Nevertheless, the confluence of energy, environmental, economic, and other strategic drivers (related, for example, to the concurrent development of advanced batteries for military applications) has led to a groundswell of interest in electric-drive technologies around the world, and to plans by almost all automakers to introduce at least some type of electric-fuel vehicle in significant numbers in the 2010-2013 timeframe. Table 1 highlights some of the plug-in-hybrid development efforts of relevance to California.

### ***Plug-In-Hybrid Development Activities***

| <b><u>Vehicle</u></b>   | <b><u>Li-ion battery</u></b>     | <b><u>e- drive equivalent</u></b> | <b><u>Status</u></b>          |   |
|-------------------------|----------------------------------|-----------------------------------|-------------------------------|---|
| BYD F3DM                | BYD LiFePO4                      | 60mi                              | \$22k in China; U.S. in 2011  |    |
| Chrysler Town & Country | Li-ion (A123?)                   | 40mi EREV                         | by 2014                       |    |
| Fisker Karma            | Adv. Li. Power Li-ion (EnerDel?) | 50mi EREV                         | \$87.9k in Jun 2010           |   |
| Ford Escape PHEV        | JCS Li-ion (doped NiOx?)         | 30mi                              | Making 5k/y in 2012           |  |
| GM Chevy Volt           | CPI (LG Chem) LiMnO2             | 40mi EREV                         | \$40k in Nov 2010; SF&DC      |  |
| Toyota PHV              | Panasonic Li-ion                 | ~12mi?<br>UCB TSRC                | Testing 150 in U.S. late 2009 |  |

**Table 1. Light-duty plug-in hybrid examples**

Many automakers state that battery development has not progressed far enough to support widespread plug-in commercialization. Nevertheless most have revealed significant development activities. For example on the plug-in-hybrid front (Table 1), General Motors (GM) appears to be making an aggressive play, to compensate for having missed the boat initially on hybrids, with the Chevy Volt, a series-electric plug-in hybrid or “extended-range electric vehicle,” (EREV) slated for production in 2011 or late 2010, although economic hardship has created monumental challenges for the automaker. Also troubled, Chrysler has nevertheless been testing plug-in prototype variants of its Dodge Sprinter Hybrid in several United States cities, and showed three plug-in-hybrid concepts at the 2009 Detroit auto show. Toyota’s plug-in-hybrid announcements are more subdued and continue to highlight current battery

limitations, but signs of development have been around for several years. For example, in 2005, the “PAPI Dream House” by Tron Architecture conceptually incorporated facilities for a Prius to both charge and provide emergency power. In April 2006, Toyota acknowledged a plug-in-hybrid development program [6], and in 2008 placed with UC Berkeley and UC Irvine two plug-in Prius research vehicles with larger nickel-metal hydride (NiMH) battery packs. Much speculation continues to surround its lithium-ion efforts, though it has previously announced that ~150 PHVs with Panasonic lithium-ion batteries will begin to be tested in the United States beginning in late 2009. Ford is developing and testing a plug-in version of its Escape Hybrid with Johnson Controls-Saft batteries. A Chinese battery company-turned-automaker, BYD (currently selling a plug-in hybrid in China) and a luxury-segment United States start-up, Fisker, also offer compelling plug-in-hybrid development examples.

Additionally, several aftermarket conversions are available to make conventional hybrids, primarily the Toyota Prius, plug-in hybrids. As currently configured for sale, the Prius’s power-assist batteries and relatively small<sup>1</sup> electric motor provide a couple miles or less all-electric driving range (AER) at speeds less than roughly 34 miles per hour without triggering the combustion engine to provide additional power and/or charge the batteries. Plug-in Prius conversions generally augment or replace the propulsion battery and thus increase the all-electric-range capability of the vehicle, but only within the limits of the original electric motor and overall control strategy. Claimed AER capabilities (at low speeds/power) for such vehicles are typically ~30 miles (for example, [7]). For the higher speed/power requirements typical of daily driving, Prius conversions blend grid electricity as available into their operation as combustion hybrids. From the time the converted vehicle is fully charged from the grid to when its depleted charge requires it to operate as a self-contained gasoline hybrid (for example, ~40–60 miles), the claimed fuel economy for Prius conversions is typically very roughly double that of the original Prius per gasoline gallon, not including the required electricity (for example, [8]). However, real-world averages over a wider array of drivers and conditions may reduce these claims significantly over time.

## 1.2. Motivation

The motivation for this paper is to propose strategies for more rapidly commercializing electric-fuel vehicles in California, based on the current set of conditions and drivers. These conditions and drivers include the status of EDV technologies, economic conditions, and the environmental and energy policy setting.

A fundamental premise for this paper is that California is at a critical juncture, where there is a key role for state and federal governments to play in facilitating one of the most significant market transformations the world has ever seen. For over 100 years, the transportation sector in the United States has been dominated by motor vehicles, which in turn have been overwhelmingly powered with internal combustion engines running on petroleum-based fuels. Seen from a high level, this system has generally served society well in terms of facilitating

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1. This is relative to what might be used in a plug-in hybrid or battery vehicle; the Prius’s electric motor provides a significantly larger proportion of total power than many other commercial “mild” hybrid models.

economic and industrial growth, but with significant negative consequences for the environment, human health, and broader geopolitical and energy security concerns.

With dramatic improvements in electrochemical batteries, power electronics, electronic monitoring and control systems, and other EDV components, the potential now exists to break away from the “technological lock-in” on combustion based vehicles that has dominated our transportation systems for the past century. But this transition will not take place without the assistance of bold policy action, precisely because of the dynamics of technological lock-in that tend to reinforce existing paradigms and make it difficult for broad market transformations to succeed.

### **1.3. Project Summary**

In order to help advance the implementation of electric fuel in California, and by extension other states and regions, this project seeks to identify promising strategies that can help to accelerate and facilitate this market transformation. The conduct of this project has attempted to involve stakeholder input at three main levels, along with additional individual discussions and consultations. These levels are: 1) a “brainstorming” and exchange-of-ideas workshop during the middle of the project; 2) individual consultations and interviews with workshop attendees/invitees and additional experts; and 3) opportunity for stakeholder review and comment on the draft of this white paper document. Follow-up comments after the final white paper document is released are also appreciated, for potential future revisions.

#### ***1.3.1. Strategies for Overcoming the First Cost of Batteries for Vehicle Purchasers***

This study discusses strategies for overcoming the significant hurdle to electric transportation fuel use presented by high battery costs. Generally speaking, strategies discussed include: reducing battery costs (for example, through vehicle design considerations), finding appropriate markets and consumers, various forms of cost financing, and offsetting costs with supplemental value—including an analysis of the net-present value of post-vehicle stationary battery use and its possible effect on battery lease payments. Before exploring these strategies, several definitions and issues relevant to the scope of this investigation are briefly presented.

### **1.4. Focus: Plug-In Combustion-Hybrid Light-Duty Passenger Vehicles**

Electric transportation fuel can be used in plug-in vehicles of two basic propulsion architecture types: plug-in hybrids and electric vehicles (EVs). In addition to the electric storage systems (for example, batteries) and electric motors used by EVs, plug-in hybrids utilize other-fueled power systems, ranging from internal-combustion engines burning gasoline to produce mechanical (“parallel”) and/or electric (“series”) drive power, to fuel cells electrochemically converting hydrogen fuel and oxygen from air into electricity.

The main contenders for near-term, widespread commercialization of electric-fuel technologies are plug-in gasoline-combustion hybrids and city EVs (battery-electric vehicles providing, and sometimes explicitly designed for, relatively short-range use, generally using smaller-than-today’s-average vehicle platforms).

Several factors reinforce the notion that plug-in hybrids face substantially lower barriers to commercialization than do battery-electric vehicles, including vehicle range, battery size and cost, required consumer behavioral change, and refueling/recharging infrastructure.

Though plug-in hybrids offer lesser electric-fuel capabilities per charge, they offer greater total vehicle range capabilities, comparable or greater to consumer expectations for conventional vehicle products. It should be noted that all vehicle products needn't have equivalent range or be marketed as conventional vehicles, and different battery-EV product variations could be offered on the basis of differential valuation of vehicle range by different market niches/segments [9]. However, because they do not rely solely on electricity, plug-in hybrids offer such electric-fuel range segmentation on an even smaller and cheaper scale with less overall consumer compromise and/or behavioral change. Further, not dependent on recharging, and thus able to utilize a sparser, cheaper, and less coordinated recharging infrastructure without significant compromise, plug-in hybrids face nontrivial but significantly lower infrastructure barriers while simultaneously benefiting from advances in the existing engine and fuel industries.

To put a finer point on these issues, despite vehicle complexity and battery challenges created from deep-discharge operation, plug-in hybrids offer lower-cost commercialization and use on most fronts, including that front most relevant to this report: the contribution of per-vehicle battery systems to upfront costs. Further, with the struggling global economy and recent oil price declines having caused disproportionate reductions in conventional hybrid vehicle sales, this is a fine point indeed for the potential of plug-in vehicle sales. Least-cost vehicles are likely needed for widest implementation. Even in absence of such extreme economic conditions and recognizing that gasoline prices will rise again, the incremental costs of plug-in vehicles, let alone battery EVs, will remain difficult to justify (for example, [10, 11]), particularly over the next couple of decades as conventional technologies improve.

For a tempering perspective on electric-fuel use relative to improvements in more conventional technologies, the following is from the *Financial Times'* 2008 discussion of a report—by former French energy industry regulator Jean Syrota, tasked to analyze options building more efficient cars—which has received a cool reception by the Sarkozy government that commissioned it [12]:

Overall, the Syrota report says that adapting and improving conventional engines could enhance their efficiency by an average of 50 per cent. It also argues that new generation hybrid cars combining conventional engines with electric propulsion could provide an interesting future alternative. Toyota has been leading the field in this sector and this week Peugeot confirmed it was teaming up with Germany's Bosch to develop new hybrid models.

By combining electric batteries with conventional fuel-driven engines, cars could run on clean electricity for short urban trips while switching over to fuel on motorways. This would resolve one of the biggest problems facing all electric cars - the need to install costly battery recharging infrastructures. At the same time the report warns that the overall cost of an all-electric car remains

unviable at about double that of a conventional vehicle. Battery technology is still unsatisfactory, severely limiting performance both in terms of range and speed.

The serious misgivings over the future of the electric car may explain why the French government appears to have spiked the report.

There may be reason to be more bullish on electric-fuel use overall. However, for these and other reasons discussed below, and to provide specificity where needed, a focus on plug-in hybrids is adopted as the default throughout this and subsequent sections—though many of the strategies explored below apply to both plug-in types and explicit discussion of battery EVs is also present. In turn, in order to further minimize barriers to commercialization and maximize potential breadth of implementation of plug-in hybrids, the scope of this report generally focuses on gasoline-combustion plug-in hybrids for light-duty passenger use. It leaves aside: 1) significant discussion of the potential use of other combustion fuels (for example, liquid biofuels or natural gas)—a somewhat separate issue; and 2) a detailed analysis of the relatively important consideration of the role of non-light-duty applications as both strategic starter market niches and in their own right (however, see subsection 2.2.3 for some discussion of niches and light-duty fleets).

## 2.0 Reducing Battery Costs

### 2.1. Reducing Battery Size and Blended-Mode Operation

The most straightforward way to reduce the hurdle presented by battery-related first costs to EDV commercialization is of course to start with low costs in the first place. Though the discussion in this subsection focuses on reducing cost by reducing a dominant factor, battery size, it should be noted that this approach is only strictly valid for a given application/product system. Small-battery applications and products are not necessarily more desirable per se than products/applications requiring larger batteries, as discussed below and in section 2.3.

Beginning at the sub-product, *component* level, battery-system costs are daunting. Although estimates indicate they will fall to several hundred dollars per kWh with high volume manufacturing, lithium-ion battery systems designed for vehicles (cells and management) remain buoyant at levels near \$1,000/kWh today. Smaller and commoditized cells optimized for other applications are somewhat cheaper on a per-kWh basis, but when used in vehicles result in the need to string together thousands of individual cells into complex module and pack configurations. Even with hybridization and/or use of small vehicle platforms, many plug-in concepts require 10–30+ kWh. Thus initial battery costs alone can eclipse the cost of the rest of the car, if not the retail price of competing whole-car alternatives. This challenges the common-sense logic of even the most supportive strategies, and has even led some to suggest standardization on packs of 10 kWh or less for near-term light-duty vehicle development.

Expanding the view, battery *system* cost considerations should also include not just batteries and onboard battery management, but recharging, reuse, and recycling infrastructures. Most of these cost considerations can also be expected to scale down with battery size: for example, smaller vehicle batteries can be recharged more effectively using a sparser, lower-power, and more conventional electrical infrastructure—overnight at home using wall sockets—whereas larger batteries might require higher-power, more costly recharging hardware to be installed at a reasonably high density before easy vehicle adoption, and high per kilogram shipping costs, important to overall recycling economics.

*Product* considerations, however, might be less easy to predict. Certainly, low-cost/small battery designs cannot be compared to larger battery designs across different products with fundamentally different capabilities or serving different niches. Even for largely similar products in largely similar markets, comparisons can be more subtle and/or require careful marketing distinctions. Just as the “full” hybridization design of the Prius allowed it to deliver high fuel economy and establish itself as a clear leader over milder designs in emerging hybrid markets, so might plug-in vehicles with larger batteries be able to provide real and/or perceived benefits that distinguish them along multiple dimensions that help to offset higher costs. Even along the relatively simple dimension of fuel savings, unknown market-significance thresholds might be important. For example, at some design point a plug-in hybrid’s battery is too small—providing product benefits such as increased fuel economy at levels too insignificant relative to a conventional hybrid—to justify the cost and effort of plugging in.

Similarly, it is complex to define the merits of plug-in hybrids using larger batteries to provide all-electric range capability and maximal fuel-economy improvements relative to cheaper designs using smaller batteries in a blended-mode operation to provide nevertheless significant

fuel-economy increases. Clearly, a plug-in hybrid providing all-electric operation is a different product in a market where city centers have combustion-free zones or times. But in a less clear context, the value of unfamiliar vehicle attributes such as all-electric range is difficult for consumers to understand, let alone assess, in advance of product offerings.

Nevertheless, in absence of such “game changing” benefit dynamics, often characterized by iPod analogies and creative destruction business metaphors, and in absence of full knowledge of what benefit levels will prove sufficient to drive adoption, the lowest-cost approach is clear: to reduce battery size. For example, a National Renewable Energy Laboratory (NREL) estimate indicates that using a blended approach may require several fewer kWh and roughly 50 percent fewer kilowatts (kW) than using an all-electric-range approach [13]. This contention is supported by the federal government’s strategy for plug-in hybrid research and development (R&D): “Fuel economy, rather than all-electric range (AER) is the key vehicle efficiency metric for the public; all other vehicle aspects must be competitive, including vehicle purchase and operating costs, for a PHEV [plug-in hybrid] to be marketable. A specified AER requirement could drive cost up and decrease the likelihood of production,” ([14], p. 3). It is interesting to note [15], however, the federal tax credit, with a kWh minimum and structure that gives maximum benefit to the Chevy Volt’s relatively large, 16 kWh pack, is seemingly at odds with this stated R&D strategy.

In summary, for a product defined roughly as direct competition to light-duty vehicle sales in California, plug-in hybrids can be expected to be cheaper and otherwise easier to adopt than battery EVs. Further, blended-mode plug-ins can be expected to be easier to adopt than those designed for large all-electric range in California markets.

Limits to downsizing plug-in-vehicle batteries include the need to have sufficient “headroom” to allow for expected performance degradation over the course of specified battery life (for example, 20 percent) and/or to avoid shortening battery life via deeper-discharge operation, perhaps incurring earlier replacement. Initial cost savings must therefore be weighed against increased costs of replacement, adjusted for discounting and progression over time down the presumably steep portion of the battery production experience curve.

The policy implications of this discussion may be important. Though large-battery plug-in vehicles would likely provide greater emissions and energy-dependence reductions, supporting commercialization through policy of lower-cost, lower-barrier technologies—for example, small-battery, blended-mode plug-in hybrids with shortened battery deployment—may lead to easier and quicker adoption of electric-fuel technologies. With initial adoption of these electric-fuel technologies, the accordant changes in marketing, consumer behavior, supply channels, etc. may facilitate larger-scale shifts to electric-fuel implementation over time.

### ***2.1.1. Vehicle Road-Load Reduction: Lightweighting, Aerodynamics, Rolling Resistance***

Expanding the systems boundary beyond the propulsion system itself and its mode of operation, an important strategy to reduce the battery size required to provide the performance requirements for a given vehicle product definition is to reduce the vehicle road loads via reductions in mass, aerodynamic drag, and rolling resistance. This can be accomplished through

use of lightweight, advanced autobody materials, low-drag design, and high-pressure, low-resistance tires, collectively capable of producing, by some estimates, an up to three-fold reduction in power and energy requirements while maintaining vehicle size, safety, and affordability, and providing other benefits that help justify the cost of their implementation (for example, [16]). A relevant example of a step in this direction is the Th!nk City's use of lightweight, recyclable expanded polypropylene [17].

Policies that support road-load reductions produce efficient vehicle platforms that reduce the power, energy, size, and cost requirements of batteries and the other electric-fuel technologies required to move them.

## 2.2. Using Cheaper Batteries

For a given battery power requirement, battery costs can be reduced by using lower-cost technologies. This can be achieved either within the realm of lithium-ion technologies—for example, by using battery chemistries or designs with shorter life, higher weight, or other compromises—or without, for example by full or partial [18] substitution of lead-acid, NiMH, or other chemistries to the extent allowed by performance requirements.

## 2.3. Production Volume

After minimizing the amount of expensive batteries required to power a given plug-in vehicle product, the next strategy is to reduce the per-unit costs of the required battery system. Per-unit costs can be reduced through materials and process improvements and by spreading costs over a larger volume of production. Production volume can be increased by targeting high-volume applications, through standardization of battery cells or modules for use across multiple applications, and, perhaps counter-intuitively given the previous discussion of minimizing battery size, through selection of applications that require large numbers of cells per application. In other words, when comparing vehicle sizes, it might make sense to commercialize relatively larger electric-drive vehicles first, thereby gaining greater cell volumes from larger kWh requirements per vehicle<sup>2</sup>.

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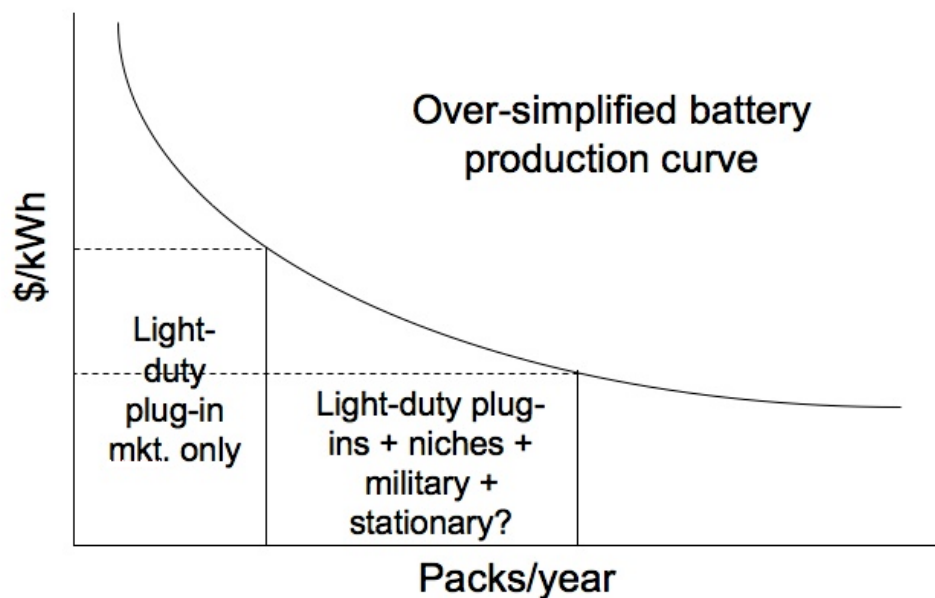
2. The cell production volume benefits per vehicle of, say, 9-kWh packs for plug-in SUVs are greater than 5-kWh packs for sedans ( $9/5 = 1.8$ ). Also, as the lifetime of battery packs decrease with increase in depth of discharge, it may be easier to meet both life and performance goals with larger packs. Consider that 20 percent SOC \* 9 kWh for an SUV is greater than 20 percent \* 5 kWh for a sedan. Further, note that improving a 20-mpg vehicle by 5 mpg saves:  $(15,000 \text{ mi} / 20 \text{ mpg}) - (15,000 \text{ mi} / 25 \text{ mpg}) = 150 \text{ gal/y}$ , whereas improving a 30-mpg vehicle by 5 mpg saves:  $(15,000 \text{ mi} / 30 \text{ mpg}) - (15,000 \text{ mi} / 35 \text{ mpg}) = 74 \text{ gal/y}$ . Thus, improving an SUV's fuel economy by a given amount can save as much fuel per year as greater absolute improvements made to a sedan. Additionally, according to an EPRI/HEVWG study ([19]

EPRI, "Advanced Batteries for Electric-Drive Vehicles: a Technology and Cost-Effectiveness Assessment for Battery Electric Vehicles, Power Assist Hybrid Electric Vehicles, and Plug-In Hybrid Electric Vehicles," EPRI, Palo Alto 1009299, May 2004.), the cost of reducing emissions with an SUV PHEV20 is -\$125,000 per ton, which is less than -\$116,000/T for a mid-sized sedan PHEV20.

Similarly, though somewhat beyond the scope of this report, it should be noted that non-light-duty-passenger vehicles and their markets/niches present interesting opportunities for commercializing electric-fuel technologies for a number of reasons, including production-volume build-up. (See subsection in 2.3 for a discussion of strategic niche marketing and fleets.) One example with a relatively more direct connection to light-duty-passenger-vehicle sales is Honda's decision to commercialize battery-electric motorcycles within two years, citing the strength of motorcycle markets during hard times [20].

Also, the military's adoption of lithium-ion technologies—which offer lower self-discharge, lighter weight, and operation over a wider range of temperatures—in a variety of vehicular and portable applications ranging from on-base NEVs to power packs for connected soldiers in the field, can help increase production volumes (and have other benefits) for civilian application. Indeed, several battery companies (for example, A123, EnergyDel, Johnson Controls-Saft, and AltairNano) are clearly competing to be key suppliers to both industries.

Figure 2 illustrates in a simplified way the potential benefits to battery cost of expanded production volume from niche, military, and even stationary markets.



**Figure 2. Battery costs per kilowatt-hour as a function of annual production**

On the mainstream light-duty-vehicle front, several vehicle manufacturers are looking to increase battery production volumes through sales to other companies: Tesla is supplying batteries to Daimler for the first 1,000 of its second-generation smart ed two-seater, Daimler in turn wants its joint-venture with Evonik to supply batteries to other OEMs [21], Toyota has announced its intention to sell its Panasonic EV joint-venture batteries to other automakers [22], and BYD is “open to licensing” its battery technology [23].

Expanding the volume strategy to whole vehicles, an unconventional example of cooperation to increase volumes for new products is the agreement between Mitsubishi and PSA Peugeot

Citroën Group for the French group to badge and sell Mitsubishi's iMiEV battery EVs in Europe:

Mitsubishi Motors had envisioned producing 2,000 iMiEVs in fiscal 2009, ramping up to 4,000 and 10,000 units in the following two years. With plans to make more than 10,000 vehicles on behalf of the French group from 2011, output will double from initial estimates. The resulting increased production will help to lower costs and boost competitiveness. (Nikkei in [24])

Policies that support volume production of electric-fuel technologies include production requirements (for example, the California Air Resources Board's Zero-Emission-Vehicle mandate or proposed pre-conditions for government bailout funds [25]), and bulk or aggregated plug-in vehicle purchase orders/requirements (for example, for government, utility, and other fleets, via EPA Act, Clean Air Act, or other policies [25]). (See subsection 2.2.3.2 for a discussion of marketing to fleets and niches.) Additionally, significant federal funds and financing are being directed at building the domestic manufacturing capabilities required for volume production (for example, the recent federal funding opportunity notice DE-FOA-0000026).

### ***Early Plug-In Market Potential in California***

In a previous analysis of early plug-in market potential in California [1], Williams and Kurani applied various common-sense constraints to eliminate unlikely households from consideration for early adoption of plug-ins and other electric-fuel technologies. 5–10 million out of 34 million Californians (26 million of driving age) appear “pre-adapted” to home recharging (for example, own residence not connected to too many units, have an income, etc.). This target segment represents those individuals that would currently appear *able* to easily adopt, and therefore more readily derive added benefits from, plug-in vehicles. It does not take into account tastes or purchase behavior. The magnitude of the target segment thus represents a maximum, though not immutable, *initial market potential*, from which sales will be drawn, forming the buy-down base for the incremental costs of the required innovations. Several differences between the target market and the driving-age/whole populations were found and highlighted, and vehicle range was discussed.

The target segment identified, and its differences with the larger populations, are neither trivially small nor overwhelmingly large. These findings would appear to justify both continued investigation of this or similar target segments—which represent more efficient research populations for subsequent study by marketing managers, product designers, and other decision-makers wishing to understand the early market dynamics facing plug-ins—as well as investigation into other market niches that can further nurture and support product development and electric-fuel innovation.

On the other hand, Axsen and Kurani [2] found that more consumers (about half) may have a plug near to where they park. But sufficiency of electrical facilities (for example, plugs and wires), and thus recharging infrastructure installation costs and level of service, are less well understood.

### **Strategic Marketing to Niches and Fleets**

Organizational fleets, despite their own heterogeneities [26] and past difficulties of regulating them to adopt alternative-fuel vehicles (AFVs), might nevertheless have characteristics that make them somewhat more tolerant of and able to benefit from—and thus have more reason to buy—plug-ins earlier than households. And, correspondingly—were marketing strategies designed to capitalize on these characteristics and plans laid to explicitly address any fleet-to-household commercialization chasm challenges that might arise—fleets might therefore be a good place to “get started” with electric-fuel innovation. This subsection explores these issues for fleets in the wider context of market niches.

Christensen’s *Innovator’s Dilemma* [27] legitimizes the process of taking disruptive technologies out of the mainstream to nurture them—both in terms of finding markets with greater willingness to pay (see subsection 2.3) as well as giving them a place for product development and volume build-up. In that sense, if innovative value is the driving force for the commercialization of disruptive products, the *Innovator’s Dilemma* helps pick the road to take (hopefully not one congested with forebodingly mature products). But what is meant by “out of the mainstream”? The primary market concepts used here are market segments and market niches.

### **Marketing Definitions**

The trouble with words like “market niche” is that you don’t know whose mouth they’ve been in.<sup>3</sup> For clarity, the following definitions are offered. Adapting [28], a “market” can be defined in terms of product, use, and consumers:  $M=f(\text{Prod}, \text{Use}, C)$ . Products, in turn, can be thought of in terms of attributes, prices, and market information:  $\text{Prod}=f(\text{Attr}, P, \text{Info})$ , and a product’s “attribute vector” (Attr) defines its “product position.” Consumers can be thought of in terms of attitudes, perceptions, psychology, demographics, etc.—for example, Moore’s [29] “psychographics.”

A “market segment” is meant to refer to a relatively homogenous subset of a market. Homogeneity makes the segment distinguishable and actionable and therefore managerially relevant. Traditionally, markets are segmented on the basis of, for example, past purchases or consumer preferences derived from surveys using importance ratings or rankings.<sup>4</sup>

On the other hand, the dictionary definition of “niche” relates to the abilities, merits, or qualities of a thing. Thus a “market niche” is meant here to be a market subset defined primarily by use, for example, as a function of use given a set of product attributes:  $\text{niche}=f(\text{Use} | \text{Att})$ . Ideally, market niches are desirous of a product’s attributes and tolerant of its weaknesses—a “safe harbor.” Note, however, that niches do not preclude the heterogeneity of consumer preferences, as market segments are meant to do.

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3. Phrase adapted from a quote by Cambridge academic Susan Owens when discussing the concept of sustainable development in 1994.

4. At an IQPC conference in Chicago in the 1990s, Jonas Bereisa of GM EV1 fame once rated the three most important attributes of cars as: #1=cost, #2=cost, #3=cupholders.

In short, a “segment” is a homogeneous subset (related to consumers), whereas a “niche” is a use/application subset (related to product attributes).

### ***Strategic Niche Marketing and Fleets***

Like biological organisms that find success in environmental niches for which they are best suited, so might new technologies like electric-fuel vehicles best compete in market niches that have a relatively high value for electric fuel’s strengths and unique attributes (for example, zero-tailpipe emissions, electric-drive benefits, potential use to supply plug-in/plug-out [30] services, and a diverse fuel production portfolio) while being relatively indifferent to its weaknesses (for example, heavy, voluminous, and/or otherwise problematic storage, limited recharging, cost). But, just as the biological organism simultaneously affects and is affected by its environment, competitors, and so forth, so should niche marketing be an active, bi-directional, and strategic endeavor. As Moore reminds us, *marketing* is an active process of creating markets for your products, while simultaneously evolving the product based on an acute attention to the consumer. It should not be conceptually reduced to *sales* into a static market. Further, he argues, market *niches* should be managed strategically, acting as beachheads that are selected for their ability to lead to expanding opportunities and build market relationships, supply chains, and consumer reference bases. These concepts might help illustrate where several previous AFV commercialization efforts went wrong: by recognizing organizational fleets as a potentially attractive niche, but failing to recognize the extent to which these markets need to be actively managed and, critically, strategically expanded.

Hearing the siren’s call of volume ramp-up, AFV market development efforts are easily lured towards the supposed harbor of organizational vehicle fleets. The logic for doing so can be compelling: large numbers of vehicles being bought per transaction into relatively controlled environments, often with centralized refueling and maintenance by trained professionals and known, often modest, mission requirements. Further, many organizations might be either highly motivated to adopt clean technologies (for example, those with a public-service or environmental component to their missions) or highly controllable (for example, government officials can lead-by-example by dictating purchasing requirement to “their own” fleets).

However, the reality of AFV commercialization has not yet lived up to its apparent potential. As mentioned, fleet managers themselves are often conservative in their attention to the bottom line and heterogeneous in their behavior [31], reducing their potential as “early adopters” and fragmenting the stocks of fleet vehicles from one promising whole into a shattered array of market subsets, segmented by behavior, psychographics, and their own unique requirements. Further, the greater-than-expected difficulty of commercializing AFVs in organizational fleets either resulted in or was reinforced by diminished enthusiasm and commitment (for example, as represented by the United States government’s neglect of EPACT requirements).

Further jeopardizing the hopes of AFV commercialization in organizational fleets was the apparent lack of a follow-on plan, particularly one supportive of strategic market expansion and supplier and consumer community building. Hoping fleets would provide the magic elixir of volume sales, little previous attention seems to have been paid to ensuring the continuing success of AFVs in fleet markets (even if EPACT were enforced), let alone to the marketing transition from organizational to household consumers of AFVs. Lacking this drive, it is

appropriate to ask not only “Were fleets a bad place to start?” but “Did we start badly with fleets?” [32].

The need to form strategic connections from one niche to another—from early markets to a beachhead in the majority to ever-expanding markets, as described by Moore (see the appendices)—was an important active-management ingredient missing from previous efforts that the authors now have at explicitly at their disposal for the commercialization of plug-ins and other electric-fuel innovations. Thus, it might be worth revisiting organizational fleets made up of predominately light-duty vehicles for the potentially beneficial role they might play in pre-household commercialization of electric-fuel technologies. Further, the strategic niche framework should be, and is being, expanded to include a wide array of non-passenger-car transportation modes, and beyond.

For example, in their argument for the consideration of marine and other forms of freight transportation as the early markets for hydrogen [33], Farrell, Keith et al. argue this explicitly in a framework emphasizing the importance of niche management. They discuss how such an approach makes the challenges more manageable by constraining the scope of the infrastructure development and concentrating the fuel demand on fewer, larger, more heavily-used vehicles confined in a geographical area along point-to-point routes with professional crews and known mission requirements and which receive high levels of engineering and operational attention. Doing so, the authors claim, will cost-effectively unlock a virtuous cycle of learning-by-doing that is needed for technologies to mature.

Indeed, the logic and benefits of introducing alternative fuels into an even broader set of transportation niches is evidenced by dozens of press releases in the AFV industry press. They include development efforts for forklifts, mining equipment, aircraft tow tractors, scooters, submarines, hummers, heavy-duty trucks, and motorcycles, as well as fleet applications for medium- and light-duty vehicles such as delivery, construction contracting, and maintenance/repair.

Nevertheless, many questions still remain about a niche approach to alternative-fuel commercialization. Can you really slide down a production-volume learning curve through a series of niches? For example, to what extent does commercializing an alternative fuel like electricity or hydrogen in a fuel-storage-unconstrained application such as marine freight help its readiness for storage-constrained applications like light-duty vehicles (LDVs)? Again, the production-volume-as-panacea approach is unlikely to work in absence of awareness of the dynamic and bi-directional changes that alternative-fuel technologies will undergo/cause in each niche or application. Further, even with an awareness of the realities of fleet conservatism and heterogeneity, to what extent can we really expect to do much better in overall magnitude with plug-ins? What expectations might be more reasonable from a fleet-as-early-adopter approach, and how might fleets become one element of an overall approach to buying down the incremental costs of new technologies? Do any of these niches have enough drive to stand on their own? And, even if they might, will they be enough to excite the continued commitment of large industries like automaking (which has heretofore appeared uninterested in fully marketing vehicles to non-mainstream markets, such as those potentially emerging as most suitable applications for city or neighborhood EVs)?

The question of whether or not fleets are a good place to start will not be resolved here, but strategic niche marketing considerations argues for their re-assessment. However, all will be for naught unless electric-fuel benefits are refined into robust value propositions that allow plug-ins and other electric-fuel technologies to move beyond niches into the profitable mainstream. Working in concert, market-development strategies and considerations for discontinuous innovations can be used as tools to aid in the early market development for electric-fuel technologies. The discussion now turns to a related topic: early / target consumers.



### **3.0 Willingness/Ability to Pay**

The previous subsections presented ways to reduce EDV technology costs. The discussion now turns to ways of making payment of given costs more palatable. First, consumer willingness and ability to pay are highlighted here and weighed against equity concerns. In following subsections financing, creative business models, and provision of supplemental value are explored.

#### **3.1. Luxury/Large Passenger Vehicle Markets**

New products with initially high costs are often developed and marketed to consumers who appear most willing and/or able to pay cost premiums and/or who have low price sensitivity, for example, as luxury items to high-income consumers. For advanced automotive propulsion systems, this might be expected to manifest in luxury-brand or certain larger vehicles, and has, to some extent, in the form of various Lexus hybrids, the Cadillac Converj concept plug-in hybrid using the Chevy Volt technology [34], etc. Further, the greater profit margins on luxury and/or large vehicles might allow a less painful loss-leader strategy for suppliers, and the necessary price increases may be less “visible” (consider for example \$6k on top of a \$38k SUV [16 percent increase] vs. \$4k on top of a \$19k sedan [22 percent increase]).

However, two factors complicate this picture. First, one of the primary benefits of electric-drive technologies is fuel-cost savings, to which luxury car buyers are not generally thought sensitive (though the “design-space elbow room” from gains in fuel efficiency can be allocated to performance and economy in varying proportions). Second, electric- and other alternative-fuel technologies have historically been compromised in range and/or other performance measures (though to a lesser extent in smaller vehicle platforms, as seems to be the increasing focus of battery EVs). These are not generally thought acceptable to luxury car buyers. These factors, though not decisive, do reinforce the importance of other aspects of the advanced-vehicle value proposition—for example, symbolism [35]—as well as the need for a more subtle analysis of willingness-to-pay that goes beyond mass-market consumer income segmentation. For example, sources of relative willingness-to-pay may be found in consumers particularly motivated to try out electric-fuel technologies for various reasons, or in non-light-duty-vehicle applications where propulsion systems are relatively expensive anyway, produced in lower volumes or with more customization, or dwarfed by other application-specific costs. Thus early-adopter marketing principles, discussed next, may be much more pertinent to marketing electric-fuel vehicles than has been historically thought or practiced in recent decades in mass-market automaking [36].

#### **3.2. Marketing Discontinuous Products to Early/Target Consumers**

This subsection on market development begins by discussing the importance of finding “value propositions” to drive electric-fuel commercialization. Spread throughout this study, the potential benefits of electric-fuel innovation are numerous and arguably compelling, yet remain too diffuse and spread across too many actors to yet be considered a value proposition in the traditional marketing sense of addressing burning consumer needs. In order to strike a marketing bull’s-eye, subsequent study of electric-fuel innovation will need to narrow the shotgun approach taken here to rifle-like precision by increasingly focusing on more specific

contexts. Nevertheless, this section argues that electric-fuel innovation presents the opportunity to break consumers and suppliers out of a self-reinforcing singular definition of vehicle products and points the way to more product diversity and differentiation. The introduction of innovative new products and services, however, requires greater attention to the early market dynamics that govern the diffusion of discontinuous technologies into the mainstream. These dynamics are perhaps more familiar to high-tech than to automotive and energy marketers.

### ***Searching for Product Differentiation***

“Killer app,” “competitive advantage,” and “value proposition.” These terms are commonly used in technology magazines, start-up business plans, and marketing campaigns for innovative products, but get less play in the automotive industry where vehicles have essentially the same set of attributes and provide largely the same set of services, with some variation between vehicle classes and option packages. The homogeneity of conventional fuel products is perhaps even higher, presenting even fewer opportunities [37]. It is not much of a stretch, then, to describe automaking as a cutthroat commodity business constantly in need of product differentiation.

Unlike some other fungible products, however, part of the reason value differentiation might appear to be lacking in the automaking industry is that modern automobiles already uniformly and affordably provide an extremely high level of comfort, convenience, and other qualities at an affordable price and under tight regulation. It is this very standard of “uncompromised mobility” that has plagued efforts to introduce immature and significantly different alternatives, which typically fall short on one or more dimensions. This has produced the precept amongst chastened veteran advanced-technology-vehicle developers that new offerings must be equal to or better than existing cars in every way.

Further, the relative homogeneity of vehicle offerings is a self-reinforcing phenomenon: consumer expectations are ratcheted tightly to a singular definition of the typical passenger vehicle, indirectly making vehicle suppliers reluctant to provide transportation products that differ dramatically in performance from their core-competency mass-market passenger vehicles, as many EDVs do<sup>5</sup>.

Plug-ins must thus fight an uphill battle in order to break into a competitive industry with mature, high-quality products and an uncompromising, self-reinforcing product definition. Even when conceived simply as clean cars and trucks, today’s plug-ins, particularly plug-in hybrids, promise to be less “compromised” than 1990s-era battery-EVs on several dimensions (for example, driving range, cost, and fast refueling for plug-in hybrids) while providing at least a taste of the palatable difference that zero-tailpipe-emission electric drive offers over other alternative fuels in internal-combustion-engine vehicles [38]. Nonetheless, they remain compromised relative to today’s gasoline vehicle options in many ways (for example, proven reliability and, particularly for the foreseeable future, price). Given they have arguably already

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5. One might speculate that—had ways been found around this self-reinforcing cycle and were 1990s-era battery-electric vehicles recognized, designed, and marketed by major OEMs not as compromised mainstream vehicles but as niche or otherwise non-traditional offerings in a diverse personal mobility portfolio—the outcome of those development efforts might have been different.

failed the precept of providing uncompromised personal mobility, plug-ins arguably must provide innovative value in order to be successfully adopted.

The opportunity exists to leverage the unique set of plug-in attributes to *clearly* differentiate them and drive their commercialization by creating *new* value propositions for the consumer. This not only offers the basis for new value propositions, but also gives automakers the opportunity to fundamentally redefine themselves and the products and services they offer and support, much as “energy companies” formally known as oil companies and soon to be known as diversified energy service suppliers are trying to do now. With these opportunities, however, come the uncertainties that accompany new “game changing” or discontinuous products and services that will have complicated and uncertain implications both for producers and consumer lifestyles. Of particular importance to market development for new products with potentially discontinuous effects on consumer and producer behavior are early market dynamics.

### ***Marketing Discontinuous and Unfamiliar Products***

Why might automakers and energy companies, with extensive market-development capabilities and experience in capital-intensive and highly regulated industries want to pay close attention to start-up issues faced by software geeks in the high tech world? Sometimes state-of-the-art business practice isn’t good enough. Christensen [27] describes the surprise many large, successful companies in several industries have faced when disruptive technologies considered unattractive by their current customer base have nevertheless succeeded, having been nurtured through rapid improvements in other markets with different priorities. He advises companies to not be beholden to customer opinions and examine opportunities to invest in seemingly inferior technologies that nevertheless have the potential to disrupt current practice.

Similarly confoundable are efforts to evaluate with consumers the value of substantively different vehicle products, particularly using traditional methods such as econometric modeling based on consumer “rational choice” methods [39]. Turrentine and Sperling [40] also discuss the inadequacies of evaluating AFV value using “rational choice” methods when faced with preference instability due to the uncertainty and unfamiliarity surrounding AFVs and their attributes, let alone any new services they might provide. Enhancing the description of the AFV purchase decision with concepts from psychology and other social-science fields, they relegate a more limited, mature-market role to the use of “rational” frameworks that rely on consumers making comprehensive and sophisticated compensatory-trade-off and cost-benefit valuations. They argue 1) the greater usefulness of thinking about consumer consideration of AFVs using a staged evaluation process that focuses first on major aspects, such as vehicle size, with subsequent evaluation of a small number of remaining vehicle candidates, and 2) the importance of early-adopter groups (in their case, described as moral/social choosers and experimenters) in their influence on later, more utilitarian consumers. A discussion of the second point can be found in the appendices.

Having acknowledged that the relative value of electric-fuel technology may be high in other applications and market contexts, the next subsection returns to the larger, more mainstream, light-duty market focus of this report and begins the exploration of creative ways to help consumers purchase electric-fuel technologies via financing and other business-model arrangements. However, one additional issue related to willingness/ability to pay should be

acknowledged for its pertinence to policymaking. A focus on high ability / willingness-to-pay consumers as a strategy for commercializing electric-fuel technologies necessarily raises equity and other concerns: in what ways can policy appropriately support costly technologies whose most immediate benefits might fall on high-income, luxury consumers, without further disadvantaging the low-income and other more susceptible segments of taxpayer citizens? Though low-cost, rapid, and responsible commercialization of low-emission, efficient electric-fuel technologies, via whatever route(s) available, would likely accrue state-wide benefits shared by most, if not all, Californians, and would advance the state towards a cleaner paradigm that reduces the overall opportunities for environmental injustice, careful consideration must be given to these issues as policies are developed.

## 4.0 Consumer Financing Mechanisms

Consumers pay for cars and their use in the various ways, each presenting a leverage point for policies hoping to support electric-fuel use. Table 2 presents some of these concepts.

|                              |  |
|------------------------------|--|
| Vehicle cost                 | Policy intervention examples                               |
| Vehicle retirement           |  |
| • (Sell)                     | Used-vehicle sales tax                                     |
| • (Trade-in)                 | Trade-in tax   |
| • (Scrap)                    | Feebates, accel. scrappage                                 |
| Vehicle search               |  |
| • Gathering info, comparing  | Social, gov't marketing                                    |
| Vehicle purchase             |  |
| • Vehicle price              | Tax rate, credits; Carbon off-sets/LCFS offsets, financing |
| • Title fee                  | Title fee rate   |
| Vehicle use                  |  |
| • Insurance                  | Pay as you drive   |
| • License, registration fees | Registration fee rate                                      |
| • Maintenance, oil, tires    |  |
| • Repairs                    |  |
| • Fuel                       | Tax rate   |
| • Tolls                      | Toll rate (for example, free)                              |
| • Parking                    | Parking rate (for example, free)                           |
|                              | Recharging provision                                       |

**Table 2. Vehicle cost elements and policy intervention examples**

For example, tax credits are available for plug-in hybrid consumers under the Emergency Economic Stabilization Act (the \$700B bailout bill) [25]. And EISA includes grants for plug-in-vehicle demonstrations and to reduce the up-front costs of various electrification projects, including forklifts, ports, and truck stops.

There also appears to be renewed and growing interest in introducing size- and revenue-neutral vehicle-purchase feebates: “In each size class, inefficient models pay a corresponding fee while efficient models earn a rebate paid for by others’ fees,” [41]. “Canada has had a feebate law in effect since 2007. Last month, several European countries adopted feebates: Finland and Ireland changed their automobile tax structure to vary based on greenhouse gas emissions, and France just implemented what’s being called the “bonus-malus” law last month,” [42].

Additional, non-monetary policy incentives can complement financial incentives, such as carpool lane access (though this value has also developed a monetary component: resale value of vehicles with carpool stickers can be significantly higher, particularly in markets like Los Angeles).

The use of various financial frameworks could help increase the value of plug ins or lower their costs. For example [3], articulates that a “real options” approach to plug-in-hybrid valuation that takes account of the fuel choice these vehicles provide can raise the break-even battery price by over \$100/kWh. New business models may speed adoption by restoring values such as these left on the table due to purchasers’ failing to value fuel flexibility. For example, a company might make an upfront payment to the vehicle owner, reducing the cost of plug-in purchase or ownership. Then, each time the vehicle is recharged, the vehicle owner pays the company a percentage of the resultant fuel-cost savings. In effect, the company purchases a percentage of the plug-in-hybrid option value and would want to make this deal if the up-front payment is less than the ultimate purchased option value. The vehicle purchaser, on the other hand, may like the deal if the up-front payment is more than the discounted cash flow value of the stream of charging payments, using the relatively high levels of discount rates that consumers often seem to apply to future energy cost savings.

Creative financing mechanisms may also be employed to help finance plug-in hybrids. A program being developed by the city of Berkeley and other municipalities to help homeowners finance solar systems presents a stimulating example. In these programs, property owners are allowed to install solar systems and pay back the city’s bond or loan fund for the cost over 20 years through their property-tax assessment. Such a scheme hopes to provide several benefits:

First, there would be little upfront cost to the property owner. Second, the upfront capital costs would be repaid through a voluntary tax on the property, thereby avoiding any direct effect on the property owner's credit. Third, the total cost of the solar energy system and energy improvements should be comparable to financing through a traditional equity line or mortgage refinancing because the well-secured bond will provide lower interest rates than are commercially available. Fourth, the obligation to pay the tax transfers with the property. (WSJ article Nov 14, 2008, p. A13)

Such schemes could be expanded to electric-fuel innovations either analogously or more directly by including home recharging facility / electrical-service-upgrade financing, or creating green-development mortgages into which recharging infrastructure—or, more ambitiously with greater complication, other plug-in hybrid investments—could be rolled.

A final example of a creative, grand, and socially progressive financing scheme articulated by Amory Lovins of the Rocky Mountain Institute suggests the creation of a financing program for low-income Americans:

Use tailored financing programs to help low-income Americans (many of whom can no longer afford personal mobility) to buy new, very efficient, highly reliable cars bundled with insurance and price-hedged gasoline. Scrap dirty old cars a few years early. Net result: a new million-car-a-year market for Detroit among customers who couldn't previously qualify for a new car; cleaner air; faster oil savings; and astonishing new employment

opportunities for low-income citizens who couldn't previously get to work. [41]

In addition to the potential environmental benefits, such a program could help cut income disparities between socio-economic groups by providing better access to jobs.



## 5.0 Battery Leasing and Third-Party Ownership

Battery leasing is a potentially powerful concept that could allow plug-ins to compete on a favorable basis, shifting the terms of the business case from upfront, capital costs to lifecycle costs, where plug-ins are hoped to be competitive. Indeed, Pifaretti (in [19], p. 4-21) claims, “[i]n Europe [battery renting] has significantly increased the sales of battery EVs.” Battery leasing would also give battery manufacturers a profit-margin incentive to make longer-lasting, recyclable batteries and drives the incentive to maximize zero-tailpipe-emission, efficient electric-fuel use. Depending on exactly who is leasing what (Table 3), challenges include multiple-party coordination for product development, standardization, marketing, sales, and service/warranty of this new way to supply mobility, including initial roll-out of sufficient support services. Additional challenges stem from (among other sources): variable use by different customers with different use and charging patterns, and multiple battery chemistries and requirements.

| Business model type   | Product: what | Product: which | Name                 | Term       | Unit          | Example  |
|-----------------------|---------------|----------------|----------------------|------------|---------------|--|
| sales (ownership)     | car           | single         | car sale             | permanent  | (all)         | dealer sale  |
|                       | battery       | single         | battery sale         | permanent  | (all)         | conversion kit sale  |
| subscription (access) | car           | single         | car lease            | per period | time          | dealer lease   |
|                       |               |                |                      | per use    | distance      | dealer lease mileage charges                               |
|                       |               |                |                      | per period | time          | Energy services company (ESCO)? utility? battery supplier? |
|                       | battery       | single         | battery lease        | per use    | veh. distance | ESCO? utility? battery supplier?                           |
|                       |               |                |                      |            | through put   | ESCO? utility? battery supplier?                           |
|                       |               |                |                      | per period | time          | airport car rental   |
|                       | car           | type           | car rental/share     | per period | time          | airport car rental   |
|                       |               |                |                      | per use    | distance      | rental mileage charges                                     |
|                       |               |                | battery rental/share | per period | time          | ?  |
|                       |               |                |                      | per use    | veh. distance | Better Place?  |
|                       | battery       | type           | battery rental/share |            | through put   | ?  |

**Table 3. Vehicle sales/subscription models and terms**

## 5.1. Battery Leasing Examples

Modec UK (modeczev.com) is a company that has designed from the “ground up,” and custom sells, a battery-EV urban commercial delivery truck, available in cab chassis, side pull-down, and box van configurations. Several dozen vehicles are in use in the United Kingdom (UK) by large companies like UPS and Tesco, FedEx has ordered 10 for their UK operations, and two are being tested in the United States. With GE Capital financing, Modec sells the vehicles with a 100,000-mi, 3-year bumper-to-bumper warranty, but leases the battery:

Our customers can enjoy peace of mind, knowing that in the unlikely event of a technical issue, Modec are responsible. We offer to replace the battery when necessary and ensure it is recycled correctly at the end of its life.

Battery lease costs depend on the annual mileage and the rental period. For example, a typical 4 year lease could be arranged. After 4 years the contract can simply be renewed with the same battery or a new one, depending on the performance of the battery. In addition, you can protect yourself from rising diesel prices by having a consistent monthly battery rental charge. [43]

Modec claims to be “agnostic” but knowledgeable about the latest battery technology, and currently offers two options: Zebra (NaNiCl, providing ~100-mi range) or lithium-ion (LiPO<sub>4</sub>, providing ~60–70-mi range and “proving popular with Modec customers”), which they claim can be exchanged via drop-down cassette in 15 minutes for an upgrade.

Media favorite and VC insider Better Place extends its business model beyond ownership and leasing of batteries (on a per mile basis) to include the implementation of a network of recharging and battery-switching stations. These extra measures further address concerns about the limited driving range of battery-only EVs. However, the measures are expected to be expensive and require complex coordination (a core of the Better Place IP position is in its control-center software) in order to properly manage increased demands on the grid. Though they comprise a more complete mobility solution for battery EVs, it is unclear how such services could be offered as cheaply as a more straightforward battery lease.

Further, such measures (opportunity charging and battery swapping stations) are unnecessary for plug-in hybrids, which can be recharged leisurely at home during off-peak hours and refueled rapidly and cheaply using existing liquid-fuel infrastructure abroad. The marginal cost savings and other consumer benefits of going completely electric would not currently appear to justify such aggressive measures in California (see also Section 2.1), where political conditions are much less extreme and consumer characteristics less favorable than in Israel. Representing an interesting if elaborate and expensive case of strategic niche marketing—ironically more akin to a subscription version of onsite production of hydrogen at refueling stations for fuel-cell vehicles—it nevertheless may help create an EV industry abroad capable of eventually finding disruptive roots in the United States. It should of course be watched, and creative innovation should not be unintentionally stifled. But given current acute economic hardships and a

presumably much lower-cost alternative pathway via plug-in hybrids<sup>6</sup>, such approaches, like vehicle-to-grid power provision, might be appropriately considered steps to be taken subsequent to initial hurdle busting in an analysis such as this one that focuses on low-cost, broadly applicable strategies for California.

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6. Low-cost plug-in-hybrid deployment might benefit from the availability of a per-mile small-battery and low-power-home-recharging lease.



## 6.0 A Strategy for the Electric Fuel Transition in California

Battery first costs present a major barrier to the commercialization of electric-fuel vehicles. The battery pack for the forthcoming Chevy Volt, for example, is the single largest determining factor for the entire vehicle's ~\$40,000 loss-leading price point. Indeed, a recent study at Carnegie Mellon University estimates the cost of the battery pack alone to be up to \$15,000 [44], equivalent to the retail cost of some conventional vehicles of not dissimilar size. Further, to provide its promised 40-mile all-electric range, the battery must be roughly twice as big (16 kWh), and thus costly, as what is available for propulsion (8 kWh), to allow for both "operational breathing room" (for example, to maintain battery life by limiting depth-of-discharge) and for capacity degradation over a 15-year, 150,000-mile lifetime—each accounting for roughly half of the unavailable capacity. Faced with such cost and design challenges, the extent to which such vehicles can be commercialized to the masses remains uncertain.

Working in concert, several strategies discussed in this section could be employed to alter the early commercialization picture for electric-fuel vehicles in California. Like the plug-in hybrid vehicles they help, these strategies straddle automotive and electrical-energy worlds, embracing their convergence. They include: battery downsizing, standardization, and leasing, with shortened initial vehicle deployment and repurposing / down-cycling into stationary use for building and grid-support services. Third-party or other non-conventional ownership arrangements might not only align incentives for battery improvements and full and responsible use, but may allow the net-present-value of battery services to be accounted for in the initial vehicle transaction, lowering costs, and easing initial design and commercialization expectations. Indeed, rate-based utility investment in batteries and their repurposing for stationary use (including infrastructure) may be justified, strengthening the ever-tightening connections between transportation and stationary energy and helping to launch a new era of electric-fuel technologies.

### 6.1. The Standard Vehicle Battery Pack

Consider a standardized vehicle battery pack with a form factor (or perhaps a few form factors) appropriate for the operation of plug-in-hybrid lithium-ion modules (say, lithium-iron-phosphate or "LiFePO<sub>4</sub>"), as well as some relatively minimal balance of plant providing for battery health and standard interfaces (for example, a voltage monitor, health / throughput meter, some minimal intelligence, and cooling and electrical connections).

If initially (that is, using today's state of technology) capable of containing 6 kWh—enough to provide a mid-sized blended-mode gasoline plug-in hybrid a roughly "15" mile "EV" range—such a pack might be expected to cost roughly \$9,000 or less in the near term at the retail level (at a conservative \$1,250/kWh for the battery modules plus another ~\$1,500 for balance of plant).

The pack could be standardized for use in only mid-sized plug-in hybrids, or to initially achieve greater economies of scale, used across multiple vehicle size classes to offer somewhat greater "electric" or "EV" equivalent range capabilities in smaller vehicles and lesser in larger vehicles. Once introduced and supply chains, distribution channels, and consumer markets established, improvements in battery technology (perhaps initially quite rapid / large) would increase the capabilities of the fixed-size standardized battery pack over time, following more conventional

product-development processes, and allow future releases to offer greater performance as markets for plug-in technologies mature.

## 6.2. The Battery Lease

At \$9,000 or less per pack during initial introduction, a significant upfront cost hurdle remains. As described previously, a battery lease could help spread those costs over the operational life of the pack, say 10 years—a reasonable minimum target before use in vehicles might normally be considered, though a challenging technology-development goal for battery suppliers. Indeed, it should be noted here that vehicular applications for batteries are demanding in several ways, including: 1) rigorous operating environment and conditions, 2) load profiles demanding rapid response and deep discharges, and low-state-of-charge operation, and 3) long design life, where, unlike consumer electronics, *end-of-life* capacity is the pertinent design criteria. Nevertheless, if the standardized pack were to be available for 10 years of automotive life for \$9,000, a \$250 lease setup fee and a 7 percent real rate of interest would yield a roughly \$130/month lease<sup>7</sup> (not including electricity or recharging infrastructure, of course)—still a significant premium to pay for a vehicle with recharge capability. How might this situation be further improved?

## 6.3. Redefining the Battery-Pack Lifecycle

In the plug-in-hybrid commercialization scenario described above, the large-format propulsion battery, a young innovation, is forced to compete in its infancy as a commodity in a cutthroat automotive supply market. Even with the help of some type of lease, which could align incentives in a such a way as to shift battery design, manufacture, provision, use, and take-back somewhat towards a more lifecycle-oriented electric-fuel-service enabler, the financing picture remains challenging, driven by high initial costs and long and demanding life requirements. Further, because suitability for automotive application is defined so rigorously, including the need to specify for an end-of-design-life capacity, a relatively high-value and capable asset emerges at the end of the financing period. What residual value might remain, and, if brought forward into the initial purchase decision, to what degree might it help ameliorate the battery lease payment?

Several opportunities for creating secondary value from plug-in hybrid propulsion batteries exist, both during its initial deployment onboard the vehicle—referred to here as supplemental value—as well as afterwards, in subsequent vehicular or stationary applications. Many opportunities would significantly complicate initial commercialization challenges. For example, supplemental use during initial vehicle deployment in applications like vehicle-to-grid, emergency, or mobile power [30], if used to a significant degree, might further tax immature battery durability and be difficult to anticipate and accommodate into the initial vehicle design requirements and consumer performance expectations. And “cascading” batteries from more demanding vehicular applications to less demanding ones—for example, from a large, new-

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7. Of course, the lease could be structured a number of ways—for example, per mile and/or bundled with a renewable electricity contract to assure no-to-low-carbon miles—each of which present a number of opportunities.

model, highly-capable, and possibly pricey OEM plug-in hybrid to a smaller, lower-expectation, possibly cheaper used-hybrid conversion, and then to non-highway vehicle niches, etc.—might increase standardization challenges and/or require complex, customized refurbishing and refitting. Nevertheless, these opportunities should be investigated.

One secondary application that might present somewhat lower and simpler initial performance, design, standardization, and other challenges might be the one-time repurposing of plug-in-hybrid vehicular battery packs into stationary electricity appliances. Such devices could be used—distributed in household garages/basements or aggregated into power centers—as power and energy storage devices providing various services to the grid, the utility, and the neighborhood electrical distribution system, as well as the building in which they were located, with benefits on both sides of the electrical meter. No longer facing portability and environmental survivability requirements, re-rated and repurposed battery packs may effectively provide valuable services years after “retirement” from plug-in-hybrid application.

#### **6.4. “Repurposing” the Pack for Stationary Use**

Consider the 6-kWh battery pack described above, initially sized based on an expected 20 percent degradation in capacity over its ten-year automotive design life. After, say, five years high-capacity service in a rigorous vehicle environment, it is “repurposed” and re-rated at 5.4 kWh with an 80 percent allowed depth of discharge for 4.3 kWh of capacity available for stationary use.

Repurposing (to re-add the dis/charge, inverter, cooling (fan), and safety capability left behind in the car) and infrastructure installation (for example, a 240V, 30+A plug and wiring with ground-fault interrupt) may cost roughly \$7,000. Annualized over ten additional years of low-average-depth-of-discharge, mild-temperature, and otherwise less-demanding remaining stationary life, leads to nearly \$1,000 in annual capital costs. Can this electric storage appliance provide value that more than covers these costs and that could be brought forward to help with the original battery-lease financing?

#### **6.5. Revenue Streams**

Once repurposed and situated for stationary use, the battery pack and its electrical storage/generation capability could provide several services, including regional grid support; avoided generation, transmission, and distribution upgrades for utilities; and avoided energy and demand charges for buildings, in addition to emergency/backup power and other customer-side-of-the-meter services.

### **Ancillary-Service Value: Regulation**

At the super-utility level, a regional grid operator, California ISO is charged with the nearly statewide, larger-scale balance of electricity supply and demand, in order to maintain the quality of the electricity being bought by consumers. In addition to the high-cost challenges presented by diurnal and yearly peaks in total electrical demand, additional “behind-the-scenes” markets, such regulation and spinning-reserves, have been created to precisely control the balance and quality (for example, frequency) of power on the grid. These markets involve paying a certain amount of reserve generation capacity to run in synchrony with the grid, or to otherwise be prepared to quickly supply (or demand /shed) grid-synchronized power in the event that it is needed to maintain power quality. Importantly, capacity employed in this manner gets paid for contracted availability whether or not energy is actually produced and used. In California, both of these markets are formed on the basis of day-ahead and hour-ahead contracts, generally using a bidding process in which the regional system operator procures capacity until a sufficient amount of power is contracted, thereby setting the price [45].

|  | <b>Response time</b>                                       | <b>Revenue payments</b>  | <b>Dispatch call frequency</b>                             | <b>Generation duration per call</b>                        | <b>Generation time (h/y)</b>                    |
|--|--|--|--|--|---|
| <b>Peak power</b>  | Medium   | For <i>energy</i> generated  | ~40–60 calls per year (back calculated from rule of thumb) | 3–5h<br>[4h]   | Industry rule of thumb for central CA: [200h/y] |
| <b>Spinning reserves</b>   | 10min  | For <i>energy</i> [\$0.03/kWh] and <i>capacity</i> per kilowatt available for contract period [\$0.007/kW-h] | [20 calls per year]  | 10min to 2h<br>[1h]  | [20h/y]   |
| <b>Regulation</b><br><b>reg. up =</b> supply electricity to grid;<br><b>reg. down =</b> draw from grid | <1min; direct control of independent system operator (ISO) | For <i>energy</i> [\$0.10/kWh] and <i>capacity</i> [reg. up&down: \$0.04/kW-h; reg. up only: \$0.02/kW-h]    | Many short calls per day                                   | A few minutes<br>[reg. up&down: 20min; reg. up only: 1.4h] | [1/10 <sup>th</sup> of time plugged in]         |

**Table 4. Grid-support services**

\*Example values from 2005 modeling done by Kempton & Tomic are included in brackets for convenience and subsequent comparison.

Building upon and adapting [46, 47] and [30], which explored the case of vehicle-to-grid (V2G) service provision for supplemental value, this subsection explores stationary battery-pack electrical storage/power provision, or battery-to-grid (B2G) services for secondary value. Table 4 summarizes some of key features of three markets possibly amenable to B2G.

Markets for peak power, spinning-reserves, and regulation require increasingly rapid response. Peak-power markets only pay participants for the energy actually supplied. In contrast, ancillary-service (spinning-reserve and regulation) markets also pay generation for being on-call and available, based on the power capacity promised over a given contract period. Thus an important determinant of both costs and revenues for a device selling services in these markets is the number of hours it is assumed it will be grid-connected, available, and on-call each day. Actual generation is typically rarely called upon each year in these markets, and even when it is, it is generally required for very short periods of time. The last column in Table 4 shows the assumed time per year a battery pack would be asked to generate energy (that is, total call time or dispatch time) for each of the three markets being considered. Taken together, these features mean that these markets are relatively difficult to serve with large, expensive, power plants, and might be better served by relatively small, agile generators and/or storage devices scattered about the electrical landscape. Further, the actual demands on a battery-pack storage/generation device selling B2G services would be relatively modest, particularly when compared to automotive use.

Peak power revenues (and therefore profits) are sensitive to the usual variety of electricity-generation factors, such as “fuel”/input prices. However, because actual energy-production levels tend to be small in regulation and spinning-reserves markets, their revenues tend not to be very sensitive to the cost of fuel inputs or energy-converter degradation. The profits for these markets are sensitive, however, to the prices offered to generation capacity for being on call and to the capital costs of the “generation” technology.

Further, because it is assumed that a given device can contract for either regulation or spinning reserves, but not both, and because previous studies and preliminary modeling indicate that regulation is likely to be more profitable for battery packs than spinning reserves (primarily because spinning reserves’ longer dispatch requirement necessitates a lower capacity rating for a limited, fixed-storage device), regulation will be analyzed below.

### ***The B2G Model of Battery-Pack Storage and Distributed Generation***

Starting from [47], this subsection describes a new model constructed to estimate B2G net revenues. (The appendices provide additional detail, including key inputs and equations.) With 4.3 kWh available when full after 5 years in automotive application as described above, the repurposed battery pack could fulfill up to an 8.6-kW, half-hour regulation call.

### ***Cost of Regulation Energy***

Assuming the stationary battery pack is available 7060 hours per year (20 useful hours per day, with one unavailable day per month), called upon an average of one-tenth of the time available, able to “generate” up to 8.6 kW at the rate of \$0.13/kWh (by buying electricity at an average price of \$0.115/kWh and storing it at 85 percent round-trip efficiency), the cost of regulation energy per year is roughly \$816 per year.

### ***Regulation Revenues***

Similarly, selling regulation energy at the same average price (\$0.115/kWh) yields regulation energy revenue of approximately \$697/year.

On the capacity front, batteries could sell both regulation-up (capacity to produce power) and regulation-down (capacity to consume power, which can be used to charge the battery). Using the California ISO's 2006–2008 regulation capacity price (regulation up plus regulation down)—which averages to \$0.033 per kilowatt capacity made available per hour contract (\$0.033/kWh)—an 8.6-kW device could earn an additional \$1,971 per year in regulation capacity payments.

This brings regulation revenue to a total of \$2,668 per year, or \$1,852 per year net of energy costs. Regulation revenues are very much a function of the capacity prices offered, as well as, to a lesser extent, the energy prices offered.

It would take about 85,000 battery packs to amount to the 2006–2008 average California ISO regulation requirement of 732 megawatts per year (MW/yr)—which is likely to rise, particularly with increased renewable portfolio standards and penetration of variable wind power. For a sense of scale, 85,000 each packs making \$1,800 per year would earn >\$150 million, though we note that revenues are unlikely to remain constant as markets begin to saturate and the value of regulation services starts to fall.

### ***Peak Power***

In order to meet a peak-power call of up to 4 hours, the full 4.3-kW battery pack could be rated at only 1.1 kW, significantly limiting the battery pack's ability to earn peak-power revenue. (Similarly, spinning reserve revenues are relatively limited by the pack's need to fulfill longer calls than for regulation.)

At 1.1 kW, 150 hours/year of peak power energy supplied at \$0.13/kWh would cost \$22/year to provide. Whereas receiving \$0.50/kWh for 150 h of peak power energy would earn the battery pack \$81/year, for revenue net of energy of \$59/year. These values are modest but at only 150 hours per year could easily be complementary with some of the other values discussed here. Further, in some markets the peak power opportunity could be significantly greater.

### ***Electricity Arbitrage***

Peak power markets represent an extreme case where the grid will pay unusually high prices for energy during a relatively small number of hours per year. There also exists an opportunity to arbitrage, or “buy low” (generally at night) and “sell high” (generally during daily peaks), on a more modest scale throughout the year, based on time-variable pricing. [48] used bins of real California electricity price (=system marginal cost) data to explore how much opportunity for arbitrage existed for a theoretical 1-kW storage device of various storage capacities. Interpolating, scaling, and building upon their results, a 4.3-kWh storage device could earn roughly \$114/year, arbitraging some 265 kWh of electricity, and assuming an average spark spread of \$0.10/kWh.

## 6.6. Wind-Power Enablement and Carbon Reduction

The availability of electrical storage could enable increased wind-power capacity and generation, currently inhibited by intermittency, variability, unpredictability, and limited coincidence with peak demand [48, 49]. By increasing use and profitability of wind power, electrical storage devices could be partly responsible for concordant carbon emissions reductions and could conceivably be given some credit for providing this service.

To begin the undoubtedly complex process of estimating and assigning some carbon-reduction value to a standardized battery pack, the following rough calculation is made. Given, as above, 4.3 kWh of storage, 353 days of availability (allowing for one day per month downtime), and 85 percent roundtrip efficiency, and assuming roughly two fills per day on otherwise “wasted” wind energy, approximately 2,600 kWh/yr of wind energy might be re-generated by the battery-pack storage device. If displacing electricity at a California average carbon intensity of, according to 2006 EIA statistics and near-term projections, roughly 0.3 metric tons of CO<sub>2</sub> equivalent per megawatt-hour (TCO<sub>2</sub>/MWh), and the low end of the range of California carbon prices predicted by a Deutsche Bank, \$15/TCO<sub>2</sub> [50], the value of the carbon reductions would amount to roughly \$12/year.

Note that, though this value stream is modest, it indicates that this strategy can begin to benefit from even low carbon prices, much lower than what might be needed to help plug-in hybrids overcome their price premium directly through fuel savings.

Further, detailed analysis of opportunities for renewables enablement or carbon reductions are needed, including study of storage both distributed across the grid or partnered with a specific intermittent asset. Such analyses would go beyond simple wind-energy accounting to include the effect of storage on improving wind-power contracts by increasing the contribution wind capacity could make to planning reserves, strategic displacement of carbon-intensive generation, and so forth.

## 6.7. Secondary-Use Value Summary and the Battery Lease

Summing the four revenue streams described above (~\$1,850/year for regulation + ~\$60/year for peak power provision + ~\$110/year from arbitrage + ~\$10/year for carbon reduction) and subtracting the ~\$7000 annualized cost of repurposing the battery pack and supplying sufficiently high-power infrastructure (~\$1000/year) yields secondary-use net revenues of over \$1000 per year for the stationary battery pack. At a 7 percent discount rate, the net present value of 10 additional<sup>8</sup> years of such revenues, beginning in year six (after five years’ service in a plug-in hybrid), is over \$5000 or nearly 60 percent of the initial capital cost of the battery pack. If such “residual” value could be brought into the lease calculation, the \$131 per month lease requiring full depreciation over ten years is lowered to a \$90/month, five-year lease. This offers both

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8. Because stationary use is significantly less demanding with lower average depth of discharge, as described above, it may be reasonable to assume that the 1 year of car life is worth roughly 2–3 years of stationary life. For example, if consistently cycling at 30 percent DOD, a battery pack might get ~30,000 cycles, the equivalent energy throughput of 9000 80 percent DOD cycles (= 3\* the 3000-cycle life at 80 percent DOD) (ZEV Panel 2007, Figure 3-2).

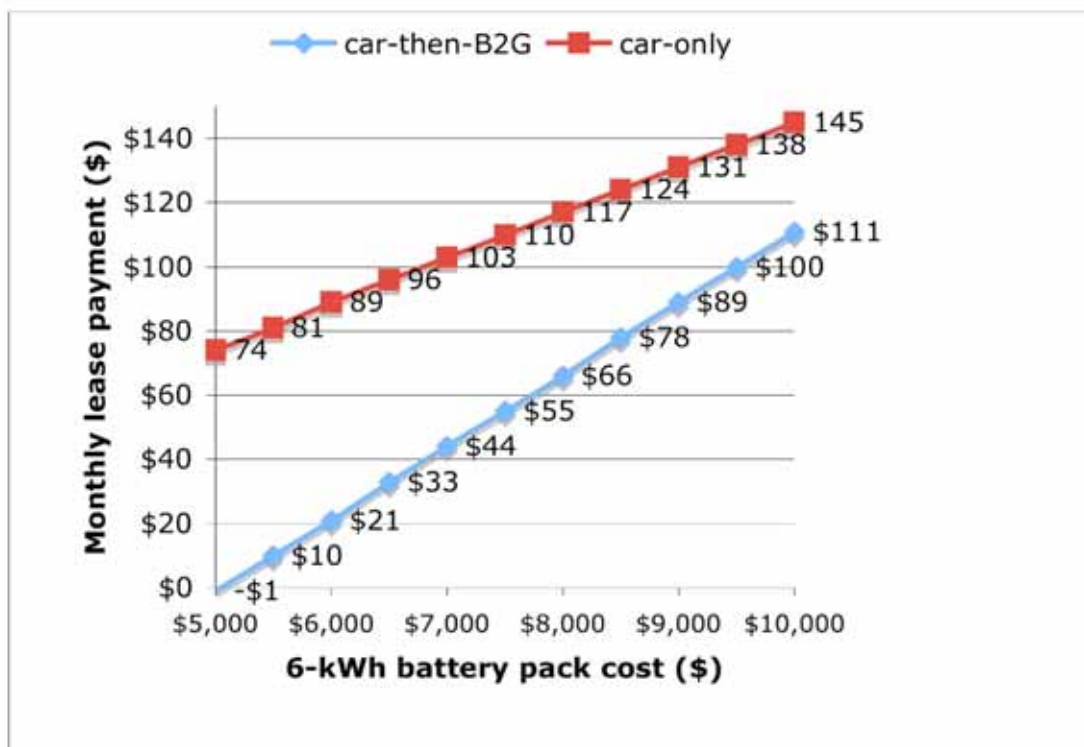
monthly savings in addition to the opportunity to upgrade the vehicle's electric-drive performance every five years with a newer, presumably cheaper and more capacious/powerful pack.

### **Sensitivities**

A comprehensive sensitivity analysis is needed in order to understand which assumptions most affect the results (and thus should be preferentially refined). Preliminary modeling reveals several sensitivities, including the following.

#### **Cost of Battery Pack**

In this study of near-term commercialization, we have made the relatively conservative assumption that a 6-kWh battery pack, with some minimal balance of plant providing for battery health and standard interfaces (for example, a voltage monitor, health/throughput meter, some minimal intelligence, and cooling and electrical connections) will cost \$9,000. Battery costs are expected by some to drop rapidly as manufacturing facilities are built for a variety of automaker electric-drive-vehicle programs. Figure 3 shows how the monthly lease payment (incorporating secondary value) varies with the assumed initial cost of the 6-kWh battery pack. Note that the lease payment drops to zero as the battery pack approaches \$5,000.



**Figure 3. Sensitivity of the lease payment to the cost of the 6-kWh battery pack**

#### **Size of Battery Pack**

Although the benefits calculated above do generally increase with available storage capacity (even when not accompanied by favorable input assumptions), bigger isn't always better: Infrastructure capital costs are lumpy and uncertain but high at high power levels (due

primarily to electrical service upgrades which include significant labor costs), dampening the benefits in high-power B2G scenarios as they pass thresholds for greater required infrastructure investment.

### **Availability**

Regulation revenue, and thus the overall results, are sensitive to variation in the number of hours per day the devices are available, on-call, and being paid for regulation.<sup>9</sup>

### **Bounding Cases and Uncertainty Range**

The strategy presented thus far has focused on a best-guess “estimate” case. Table 5 summarizes this case, as well as presenting bounding cases: a “low” case for a 3-kWh battery pack and unfavorable input assumption values made throughout, and a “high” 9-kWh case with favorable assumptions.

| <b>Battery-to-grid (B2G) value, per y</b> | <b>“Low” (3 kWh with unfavorable inputs)</b> | <b>“Estimate” (6 kWh)</b> | <b>“High” (9 kWh, favorable inputs)</b> |
|---|--|---------------------------|---|
| Regulation revenue covering energy costs  | \$227  | \$1,852                   | \$7,172                                 |
| Peak-power rev. covering energy           | \$6  | \$59                      | \$174                                   |
| Arbitrage revenue covering energy         | \$24   | \$114                     | \$323                                   |
| Carbon avoided by wind storage            | \$0  | \$12                      | \$198                                   |
| Annualized infra. capital costs           | -\$629                                       | -\$977                    | -\$1,660                                |
| Net rev., covering infra. capital         | -\$373                                       | \$1,059                   | \$6,207                                 |

**Table 5. Battery-pack grid-support-value estimates, per year, and illustrative uncertainty range**

## **6.8. Other Unquantified Values**

Many other potential values have not yet been quantified here. Additional opportunities for battery-to-building (B2B) and B2G services exist. A report by Sandia National Laboratory [51] and *Small is Profitable: the Hidden Economic Value of Making Resources the Right Size* [52], both published in 2002, lay foundations for evaluating many of these potential values, and some of

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9. The results are not particularly sensitive to variation in the number of days the battery packs are available per year, perhaps simply because the variation thought reasonable to explore here is much smaller on a percentage basis when compared to the number of revenue hours per day.

the analysis remains pertinent today. Potential sources of additional value include, but are not limited to<sup>10</sup>:

- Transmission, distribution, and generation support and upgrade deferral.
- Other ancillary / grid services.
- Other aspects of renewables firming and carbon reduction.
- Power reliability.
- Residential and commercial load following.
- Uninterruptible and/or high-quality power requirements, for example data centers or telecomm.
- Demand-response capacity and deployment.

The Sandia report focused on NiMH batteries, but suggested that the results are likely to be broadly applicable to other chemistries. Of the applications studied, the report identified no “show stoppers” and four “possible” applications for used EV batteries: transmission support, light commercial load following, residential load following, and distributed node telecommunication backup. Residential load following and telecomm backup were considered “favorable” because the lifecycle costs were estimated to be below the low end of the calculated value spread.

Additionally, recycling and end-of-life disposal—whether initially an additional form of residual value or a necessary cost (for example, due to the cost of shipping heavy batteries to recycling/disposal centers)—should be examined and compared across strategies.

## **6.9. Further Observations on Battery-to-Grid (B2G) Services**

The strategy described above clearly is predicated upon several assumptions and pre-conditions, notably presenting challenges for battery standardization, coordination amongst several parties, and the accessibility of value in grid-services markets to battery-pack storage devices. Speaking to the latter point, [5] makes several policy suggestions, including:

The [California ISO] Operating Procedure G-213 describes the process for certificating generating units, curtailable demand, system resources, and black start testing. This procedure will need to be modified to include the requirements for certificating storage facilities, (p. 4).

Recent studies have shown that fast regulation units appear to provide greater value than slow units, and there may be justification for added compensation to fast regulation units, (p. 3).

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10. *Small Is Profitable* includes discussion of hundreds of potential sources of value that should be explored further.

At the present time, no investment tax credits are available for storage facilities. The [California ISO] believes that investment tax credits could provide a valuable incentive for financing the deployment of storage technology, (p.4).

These and other changes would help realize the strategies described in this study and drive electric-fuel commercialization by enhancing battery value.

Nevertheless, it is still a valid question to ask, “So is B2G an attractive opportunity?” On one hand, some of the annual net revenues offered by selling grid-support services appear modest. Will they provide enough motivation to various required actors, either in terms of shared margins or embodied in properly accounted-for costs? On the other hand, netting even a few hundred dollars per year with system-wide benefits for the electrical grid and commercialization benefits for electric-fuel vehicles may seem a “no-brainer” to some. Or, from a more academic point of view, if the assumptions in this analysis are a reasonable start, with sufficient conservatism to help balance the effect of simplifications and uncounted or unforeseen additional costs, one might argue that the overall promise of battery-pack storage/generation is at least good enough to justify its continued study.

Next, one might ask, “What might make the margins look better?” One possible approach is aggregation:

### **B2G Aggregation**

The residential case is perhaps a relatively simple case in that it would involve individual households having the freedom to make individual decisions about how to use, or let utilities use (see next section) their garages/basements and what costs to bear for what level of plug-out services they desire. In most other regards, however, it may be challenging to implement. For example, it requires each battery pack to bear the costs of relatively high-power B2G infrastructure and requires coordination between the grid, the independent system operators, and every household selling B2G services. Although this may be possible and profitable, particularly as smart grid technology is deployed and precedents are set for, for example, utility control of household appliances, the residential case might be viewed by some as a high-cost launching point for these markets and services.

The residential case requires sophisticated aggregation of *transactions*, much as cell-phone and other companies manage for large numbers of customers, sometimes at quite narrow margins. Initially for battery-pack distributed generation, however, *spatial* aggregation might be attractive. Whether initially for publicly-owned or privately-owned battery packs, spatial aggregation into “battery-pack power plants” or demand-response units—though requiring the integration of a diversity of packs—might offer various benefits. These include the ability to spread infrastructure costs, simplify coordination, limit bi-directional power flow centers and the need for disaggregated time-sensitive price signals, aggregate capacity and energy supply into utility-friendly and distributed-generation-hardware-friendly units (for example, megawatts), and aggregate B2G benefits. It could also open up additional, related opportunities, such as green branding and other product differentiation, reduced commercial demand charges, and strategic load shedding (especially off congested distribution trunks). Alternatively, a wind

farm might choose to aggregate storage capability to save otherwise curtailed carbon-free power, smooth intermittency and otherwise present a more profitable face to the utility grid.

## 7.0 Utility Ownership and Rate Basing

Utilities would appear to be a prime candidate to play a major role in implementing the strategies just described. They have access to nearly every potential consumer in California, existing billing relationships, a unique understanding of the electrical grid, and a necessarily central role in electric-fuel-vehicle charging—not to mention the potential direct benefits they might accrue from electric-fuel commercialization and stationary battery-pack service provision. All of these and related factors would appear to make utilities central to, if not suited for, facilitating battery third-party-ownership, leasing, standardization, redeployment, and use in transportation and stationary grid-connected applications (for example, either in their service area, or collectively through a state-wide fund or coordinating organization).

But are such roles appropriate for these regulated, monopolistic entities? The answer to this question begins in the delicate balance between two subdivisions of section 740.3 of the California Public Utilities Code. On the one hand, subdivision (a) directs the evaluation and implementation of policies “to promote the development of equipment and infrastructure needed to facilitate the use of electric power and natural gas to fuel low-emission vehicles.” It explicitly includes “The sale-for-resale and the rate-basing of low-emission vehicles and supporting equipment such as batteries for electric vehicles and compressor stations for natural gas fueled vehicles.” On the other hand, subdivision (c) requires that:

[T]he commission's policies authorizing utilities to develop equipment or infrastructure needed for electric-powered and natural gas-fueled low-emission vehicles shall ensure that the costs and expenses of those programs are not passed through to electric or gas ratepayers unless the commission finds and determines that those programs are in the ratepayers' interest (CPUC Section 740.3).

Nor can these policies set up utilities to “unfairly compete with nonutility enterprises,” a clause that may have a distinct chilling effect on the extent and nature of utility involvement. For example, battery packs that are used to provide regulation would compete with current regulation service providers, and these effects would have to be factored into the consideration of the various forms of potential utility involvement.

Thus, the competing directives in principle already allow utilities to support, even sell, electric-fuel technologies, and allow those costs to be spread over its entire base of customers via electricity rates—so long as such support is in the ratepayers' interest and does not represent unfair competition. For a frame of reference, were 85,000 6-kWh battery packs (roughly enough to meet current regulation needs in California, *ceteris paribus*) bought at \$9,000 each, the costs spread over the 250 billion kWh of electricity used in California in 2005 ([energyalmanac.ca.gov](http://energyalmanac.ca.gov)) would amount to roughly 0.3 cents per kWh, or about \$20 per capita. However, these battery packs, both through their role in smart charging and by providing grid services, potentially offer many significant benefits to grid operation, investment requirements, etc. Only a fraction of these benefits have been discussed in this study (for example, a large potential for location-specific distribution support, (other) investment deferral, demand-response, and reactive power might exist—see also Section 2.6.8). But, again, many of these benefits straddle the competing policy goals through interpretation. For example, Kempton points out that direct or indirect

utility participation in ancillary service markets might be construed either as competition with existing ancillary service merchants or as a way to lower systemwide costs [53].

Nevertheless, a case could be made in the interest of ratepayers for investment and / or participation in the strategies described here, or at the least for the large fraction of elements most directly relevant to system-wide benefits and lowered system costs. Further, policy direction at the federal level may clarify any ambiguities that remain in the California Public Utilities Code. EISA changed Public Utility Regulatory Policies Act (PURPA) regulations to suggest that states consider authorizing smart-grid technologies, which explicitly include storage, distributed generation, and plug-in vehicles:

Each State shall consider authorizing each electric utility of the State to recover from ratepayers any capital, operating expenditure, or other costs of the electric utility relating to the deployment of a qualified smart grid system, including a reasonable rate of return on the capital expenditures of the electric utility for the deployment of the qualified smart grid system (PURPA § 111(d)(16)(B)).

Thus utilities might be allowed, if not encouraged to:

- Rate-base battery purchases, including used and new electric-fuel-vehicle batteries, for key utility grid applications such as the repurposing strategy described here.
- Require initial (that is, for a few years) utility purchases of new electric-fuel-vehicle batteries produced in California, helping to establish local manufacturing and build scale economies and learning.
- “Bundle” placement of electric-fuel-vehicle batteries with household solar installations to help smooth the solar contribution and mitigate residential solar cluster effects.

These strategies, the elements of the strategy discussed and analyzed in the previous subsection, and others might be pursued by utilities to spur and promote electric-fuel implementation. In doing so, such strategies look to offer direct benefit through realization of various value flows as well as indirect benefit from their role in helping to catalyze the transformation of transportation energy systems. However, such activities raise concerns not addressed here in depth—such as anti-competitiveness, conflict-of-interest, cross-subsidization, and transparency—that may require high-level policy clarification and prioritization. Further, the exact nature and extent of utility involvement in a transition to electric fuel will have to be determined in the larger context of an evolving discussion about the appropriate role of these regulated monopolistic entities.

## 8.0 Summary and Recommendations

This study discusses strategies for overcoming the significant hurdle to electric transportation fuel use presented by high battery costs. Though many of the strategies presented here apply to, or explicitly include, battery-EVs, a non-exclusive focus on plug-in hybrids is adopted for specificity where needed. Less costly, less compromised in performance, requiring a sparser and cheaper infrastructure, less disruptive to consumer behavior, and able to benefit from existing fuel and engine systems as they improve over time, plug-in-hybrid vehicles present lower barriers to commercialization. This is despite increased challenges presented by deep-discharge battery operation and the complicated marriage of combustion-mechanical and electric drivetrains, and despite the greater emissions and energy-dependence reductions provided by large-battery designs.

Policies aimed at cost-effectively and rapidly supporting the initial transition to electric-fuel and plug-in-vehicle technologies should equally focus on plug-in hybrids, while maintaining frameworks open enough to allow niche and subsequent development of battery-EV markets and technologies. Particularly in these economic times, measures with significant costs that go beyond “raising the tide to lift all boats” in the electric-fuel world to overcome challenges specific to battery EVs may not be in the broadest interest of efficiently supporting wide, rapid, cost-effective initial electric-fuel implementation in California. (Other perspectives and other policy goals, of course, may lead to other conclusions—for example, goals to move strictly “beyond oil” or “to zero emissions.”)

Strategies discussed here include:

- Reducing battery costs:
  - Reducing battery size for a given product definition:
    - For example, via small-battery, blended-mode plug-in hybrids.
    - By supporting the development of efficient, low-load vehicle platforms that minimize mass, aerodynamic drag, and rolling resistance while maintaining size and safety.
  - Increasing volume by:
    - Targeting high-volume applications (for example, light-duty passenger vehicles).
    - Possibly targeting high-cell-count *applications*, once the overall battery-pack size has been minimized for each candidate application.
    - Standardization (for example, of battery cells and modules, possibly into packs initially capable of containing <10 kWh of energy), to the extent practicable.
    - Use in multiple applications and products, for example:
      - Supplying electric-drive technologies to other vehicle marketers.
      - Finding volume and other synergies in non-mainstream (for example, fleet), non-light-duty vehicle, or even non-civilian markets.

- Finding appropriate markets and consumers, through:
  - Capturing market beachheads (for example, in mainstream markets, or in fleet, non-light-duty vehicle, or even non-civilian applications) for use in strategic niche marketing campaigns with subsequent expansion.
  - Identifying early adopters, for example:
    - In mainstream consumer markets (for example, the roughly one-third of Californians that appear pre-adapted or easily able to use and benefit from plug-in vehicles without inordinate cost or effort).
    - With greater willingness/ability to pay (defined not just by income in mainstream markets, but by early-adopter/ niche-market status).
- Various forms of cost financing:
  - Using policy levers at any of the multiple points in the vehicle retirement, search, purchase, and use cycle where consumers pay for their cars to ease electric-fuel adoption, such as tax, feebate, emissions-reduction-credit, and non-monetary incentives.
  - Creative financing mechanisms incorporating, for example, options value, property-tax/ mortgage instruments, or social criteria (creating new vehicle markets for low-income Americans).
- Battery leasing:
  - Shifting consumer costs from upfront to monthly, reducing consumer uncertainty about battery life and fuel volatility, and shifting ownership to the supplier or third party (for example, battery supplier, ESCO, or utility), thereby creating a profit-margin incentive for low-cost, durable, and recyclable battery development and a user incentive to maximize use of zero-tailpipe, efficient electric fuel.
- Offsetting costs with supplemental and/or secondary value, including the net-present value of post-vehicle stationary battery use, discussed next.

When considering plug-in-hybrid commercialization in isolation, the large-format lithium-ion propulsion battery, a young innovation, is forced to compete in its infancy as a commodity in a cutthroat automotive supply market. Even with a lease, the picture remains challenging, driven by high initial costs and long and demanding life requirements. Working in concert, several strategies could be employed to alter the early commercialization picture for electric-fuel vehicles in California. Like the plug-in-hybrid vehicles they are designed to help, these strategies straddle automotive and electrical-energy worlds, embracing their convergence. The combination examined here includes: battery downsizing, standardization, and leasing, with shortened initial vehicle deployment (five, versus 10+, years in the vehicle) and repurposing/ down-cycling into stationary use as electrical storage/ generation devices for building and grid-support services. Conservatively assuming high, pre-volume battery costs, even the subset of values explored here—regulation, peak power, arbitrage, and some carbon reduction credit—promise to lower battery lease payments while simultaneously allowing vehicle battery upgrades and profitable repurposing of vehicle batteries for stationary use.

Third-party (for example, ESCO or utility) ownership arrangements and battery leasing might not only align incentives for battery improvements and full and responsible use, but may allow the net-present-value of these and other battery services to be accounted for in the initial vehicle transaction, lowering costs, and easing initial design and commercialization expectations.

Using the case analyzed in subsection 2.6 as an example shows that, if such “residual value” for a mid-sized plug-in-hybrid battery could be brought into the lease calculation, a \$131-per-month, car-only lease requiring full depreciation over ten years is lowered to a \$90/mo, five-year lease in the repurposing scenario. Conservative battery costs were assumed, and lower costs would improve this picture dramatically (for example, the required lease payment goes to zero as the 6-kWh pack costs approaches \$5000 rather than \$9000, and in a bounding scenario combining several reasonable but optimistic assumptions the value more than covers the lease payment by several hundred dollars.) This offers both monthly savings in addition to the opportunity to upgrade the vehicle’s electric-drive performance every five years with a newer, cheaper and more capacious / powerful pack.

Further, such “battery-to-grid” or B2G devices could not only provide valuable services needed by existing statewide grid-support markets, but could provide additional value not analyzed here. Customer-side-of-the meter benefits, demand-response capability, improved utility operation, deferred grid upgrades, and further support of the profitability and penetration of wind power and other carbon-reduction measures, for example, could greatly improve these already intriguing prospects. End-of-life recycling and disposal must also be considered.

Of course, the realization of these benefits is predicated upon several assumptions and pre-conditions, requiring coordination, standardization, and granting B2G units access to several existing and future markets. Initial policy steps already identified that would allow or improve the strategies like those described here include modifying certificating procedures to include battery storage devices as CAISO generating units, further rewarding fast-response units in proportion to their operational and other benefits, and providing investment incentives [5].

Additionally, further analysis should weigh the benefits of implementing household/building B2G (in both the current context and the context of the coming “smart grid” wherein household device control may be implemented for other reasons anyway) versus spatially aggregating B2G units into “battery-pack power plants” or demand-response units, which should have economies of capital, operational, and transactional scale, and possibly simplify certain challenges.

Utilities and other grid entities are prime candidates to play a major role implementing these strategies. Not only do they have a unique understanding of the grid and will necessarily be central to plug-in vehicle recharging, they have billing access and existing relationships with households throughout California, where most electric-fuel transactions will likely take place. Given the many potential benefits to the grid, and the unique position utilities occupy, rate-based utility investment in vehicle/B2G batteries may be justified. Action appears to be at least arguably allowed by the CPUC code, and possibly encouraged by national PURPA “smart grid” regulations, so long as competitiveness and the interests of the ratepayer can be maintained. Clarification of these policies, and perhaps directing the in-depth investigation of specific manifestations of the strategies such as those discussed here, would strengthen the ever-

tightening connections between transportation and stationary energy and spur a new era of electric-fuel technologies.

As battery costs are expected to fall over time, efforts should focus on reducing barriers to adoption in the near term in order to establish markets, supply chains, and infrastructure, and build production volumes. Battery lease models offer one potentially powerful mechanism for helping to establish a framework for capturing battery values throughout their life cycle. Private and public involvement, through battery leasing, establishment of stationary applications for plug-in-vehicle batteries, and other related efforts to help provide recharging and electric power metering infrastructure, could be important to improving the likelihood of success of the current attempts to commercialize electric-fuel vehicles in California.

## Appendices

### Workshop Participant List

California Electric Fuel Implementation Strategies (CEFIS) Workshop

November 12, 2008, University of California at Berkeley

| Name               | Affiliation            |
|--------------------|------------------------|
| Alexander, Marcus  | EPRI                   |
| Battaglia, Vincent | Berkeley Lab           |
| Bedsworth, Louise  | Public Policy Inst./CA |
| Bevan, Analisa     | ARB                    |
| Boyce, Bill        | SMUD                   |
| Brooks, Alec       | Google.org             |
| Chhaya, Sunil      | EPRI                   |
| Garas, Dahlia      | UCD PHEV Center        |
| Gremban, Ron       | CalCars                |
| Harty, Ryan        | Honda                  |
| Hayden, Robert     | SF Dept. of Env.       |
| Jungers, Bryan     | ITS Davis              |
| Kammen, Dan        | UCB                    |
| Kempton, Willett   | Univ. of Delaware      |
| Lemoine, Derek     | UCB ERG                |
| Lipman, Tim        | UCB TSRC               |
| Lutsey, Nic        | ITS Davis              |
| Margolis, Jonah    | Energy Commission      |
| Mazy, Anthony      | CPUC                   |
| McCarthy, Ryan     | ITS Davis              |
| McKinney, Jim      | Energy Commission      |
| Misemer, Philip    | Energy Commission      |
| Monahan, Patricia  | UCSUSA                 |

|                   |                   |
|-------------------|-------------------|
| Newman, John      | McKinsey and Co   |
| Pearson, Leif     | V2Green/Gridpoint |
| Proudfoot, Alec   | Google.org        |
| Quong, Spencer    | UCS               |
| Schewel, Laura    | RMI               |
| Schultz, Don      | CPUC              |
| Schwartz, Peter   | Cal Poly SLO      |
| Scott, Craig      | Toyota TMS        |
| Sexton, Chelsea   | Plug-in America   |
| Shears, John      | CEERT             |
| Sheikh, Nadeem    | McKinsey and Co.  |
| Sperling, Dan     | ITS - Davis       |
| Taylor, Dean      | SCE               |
| Thesen, Sven      | Better Place      |
| Ward, Justin      | Toyota TEMA       |
| Weinert, Jonathan | Chevron           |
| Williams, Brett   | UCB TSRC          |
| Wolf, Jason       | Better Place      |
| Zambrano, Saul    | PG&E              |

## The Technology Adoption Life Cycle

Early adopters/lead users play an important role in the commercialization of new technologies and merit close attention. In order to examine the adoption of a new technology over time, diffusion-of-innovation (DOI) theory [54] depicts the diffusion of the product throughout the consumers in a marketplace using a technology-adoption-life-cycle (TALC) framework. Graphically, the technology adoption life cycle idealizes the marginal level of consumer adoption over time as a bell-shaped normal distribution. Assuming that, on average, consumers adopt plug-ins at time  $t$ , as there are in general a large number of factors that could contribute to a given consumer adopting later or earlier than  $t$ , the normal distribution is an appropriate descriptive device. Thus, the bell curve for plug-in adoption can be drawn with the number of consumers on the y-axis, time on the x-axis, and centered at a time  $t$  when the most consumers simultaneously choose to adopt. Consumers to the left of the mean time  $t$  adopt earlier than average, those to the right adopt later. The TALC further assumes the normal distribution can

be divided into several groups of consumers. The “majority,” appropriately, includes the bulk of consumers (for example, those within two standard deviations on either side from the mean value) and is divided by the mean value into the “early majority” and “late majority.” Those outside of the majority, analogous to the statistical notion of outliers, are considered “laggards” if very late adopters or “early adopters” (and “innovators” if extremely early).

Innovators are the critical “importers” of an innovation into a group (Rogers in [55], p. 32). Often, the slowness of getting technology adoption started is further highlighted by the use of a slightly asymmetrical curve, whereby the “innovator” tail builds more slowly (at a shallower angle) over time than the number of laggards declines; the left half of the curve may also be larger (that is, consisting of more consumers) than the right half.

### ***The Modified Technology Adoption Life Cycle***

As Kurani, Sperling et al. point out (ibid, p. 46) it is technically not possible to identify “early adopters” a priori, because they are defined relative to others only after those others have actually adopted the technology. However, this fact has not deterred quantitative speculation and the, perhaps more interesting, qualitative use of the TALC as a framework for understanding early market dynamics. Notably, Moore [29] formulates a strategy for high-tech marketing based on a DOI technology adoption curve divided into more discrete but familiar pieces: early-market consumers, consisting first of innovators and early adopters, and mainstream-market consumers, consisting of the early majority, the late majority, and laggards. These pieces, and the gaps he artfully chops and describes between them, emphasize psychographic<sup>11</sup> differences between consumer types that he argues should be explicitly acknowledged and embodied into marketing strategies in order to assure a behavior-changing technology’s continued march through the adoption process towards profitability. In particular, he emphasizes the deadly crossing that must be made between early and majority consumers. It is one he describes as requiring the careful planning of a D-Day attack, complete with an invasion force honed to capture critical market beachheads that will give them a foothold in profitable mainstream markets. Several lessons embodied in those analogies are beyond the scope of this study but future work may prove them valuable for the commercialization of discontinuous vehicle technologies such as those that supply electric-fuel services.

Departing from Moore’s focus on consumer psychographics, but building on his modified technology adoption life cycle model, Figure 4 illustrates a technology adoption curve distinguishing early from majority consumers, where the red vertical line separating the two represents Moore’s chasm. For simplicity, however, the y-axis represents the number of vehicles adopted, not number of consumers adopting. The groupings thus represent the cluster of vehicles bought by, say, the early majority.

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11. Psychographics are a combined set of demographic and psychological characteristics of consumers.

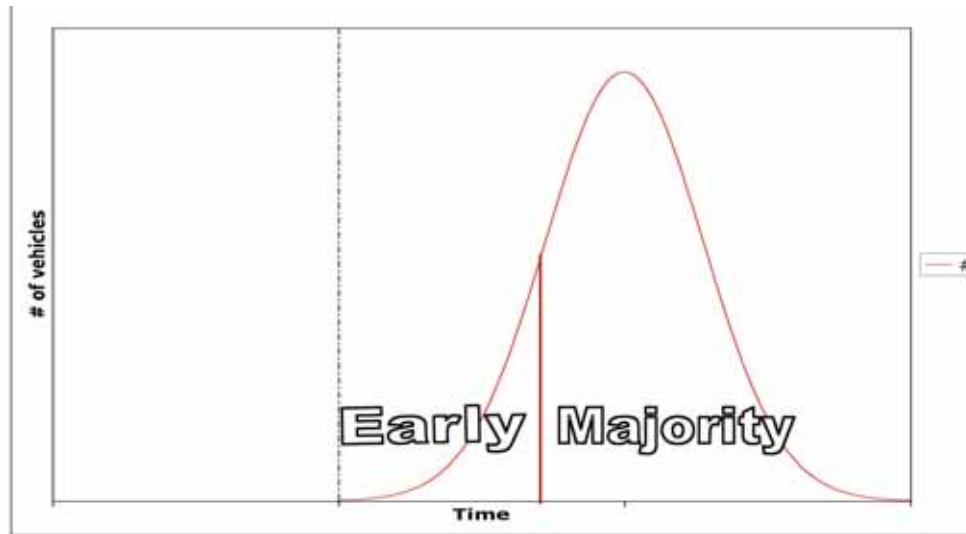


Figure 4. Plug-in vehicle adoption: early vs. majority consumers<sup>12</sup>

## Ancillary Services Calculation Detail

### Key Inputs

| INPUTS (common)                         | Low     | Estimate | High     |
|---|---------|----------|----------|
| CAPITAL                                 |         |          |          |
| Battery pack (electric fuel tank)       |         |          |          |
| Initial cost                            |         |          |          |
| cost of battery (per kWh)               | \$1,250 | \$1,250  | \$1,250  |
| size of battery (kWh)                   | 3.0     | 6.0      | 9.0      |
| cost of balance of battery pack         | \$1,500 | \$1,500  | \$1,500  |
| total battery pack cost                 | \$5,250 | \$9,000  | \$12,750 |
| In car                                  |         |          |          |
| design life in car (y)                  | 10      | 10       | 10       |
| depth of discharge allowed in car       | 0.70    | 0.80     | 0.85     |
| initial available capacity in car (kWh) | 2.1     | 4.8      | 7.7      |
| In house                                |         |          |          |

12. Note that “early” in DOI terminology can be confusing. It is used in a relative sense; thus there is an “early majority” that are “early” adopters (relative to the rest of the majority, but who are not “early adopters,” the group defined as “early” relative to the group of adopters taken as a whole).

|  |          |          |          |
|--|----------|----------|----------|
| time in car (y)  | 5        | 5        | 5        |
| capacity degradation in car (per y)                      | 0.971    | 0.978    | 0.985    |
| capacity remaining after car (kWh)                       | 2.59     | 5.37     | 8.34     |
| depth of discharge allowed in house                      | 0.70     | 0.80     | 0.85     |
| available capacity in house (kWh)                        | 1.81     | 4.29     | 7.09     |
| Annualized costs   |          |          |          |
| discount rate  | 0.1      | 0.07     | 0.04     |
| life factor (B2G cyclelife / car cyclelife)              | 1        | 2        | 3        |
| ENERGY   |          |          |          |
| cost of "fuel" (per kWh)                                 | \$0.140  | \$0.115  | \$0.100  |
| kWh in / kWh out   | 0.79     | 0.85     | 0.92     |
| cost of e- out (per kWh)                                 | \$0.18   | \$0.13   | \$0.11   |
| REGULATION   |          |          |          |
| dispatch/contract ratio 0.2                              |          | 0.1      | 0.05     |
| capacity price for reg. up+down (per kW-h)               | \$0.026  | \$0.033  | \$0.040  |
| regulation energy price (per kWh) = fuel cost            |          |          |          |
| from above   | \$0.1400 | \$0.1150 | \$0.1000 |
| total CA regulation required, up+down (MW/y)             | 700      | 732      | 900      |
| PEAK POWER   |          |          |          |
| peak-power demand (h/y)                                  | 60       | 150      | 200      |
| price of peak power (per kWh)                            | \$0.40   | \$0.50   | \$0.60   |
| ARBITRAGE  |          |          |          |
| "spark spread" including transmission & losses (per kWh) | \$0.08   | \$0.10   | \$0.12   |

## Equations

The following equations are adapted from [47].

COSTS (c) in \$ (per year)

$$c = (\text{cost/unit energy}) * (\text{energy dispatched}) + \text{annualized capital cost}$$

Cost/unit energy (ce-out) in \$/kWh generated

$$\text{ce-out} = (\text{cost of fuel}) / (\text{efficiency of fuel/input-to-AC-electricity-out conversion})$$

Energy dispatched (Edisp) in kWh

see energy sales, below

Annualized capital costs (cac) in \$/y

$$\text{cac} = (\text{cost of capital, cc}) * (\text{capital recovery factor, CRF})$$

Capital recovery factor (CRF)

$$\text{CRF} = d / (1 - (1 + d)^{-n}), \text{ where } d = \text{discount rate, } n = \text{number of years}$$

REGULATION REVENUES (r) in \$ (per year)

$$r = \text{capacity payment} + \text{energy sales}$$

$$\text{Capacity payment (\$)} = \text{pcap} * P * \text{tPLUG}$$

$$\text{pcap} = \text{capacity price (\$/kW-h)}, P = \text{power (kW)}, \text{tPLUG} = \text{time plugged in and available (h)}$$

$$\text{Energy sales (\$)} = \text{pel} * \text{Edisp}$$

$$\text{pel} = \text{electricity price (\$/kWh)}, \text{Edisp} = \text{energy dispatched (kWh)} \approx P * (\text{dispatch time, h/y})$$

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## Glossary

|                   |   |
|-------------------|---|
| AB1493            | Pavley Law  |
| AB32              | Global Warming Solutions Act                                      |
| AER               | all-electric driving range  |
| AFV               | alternative-fuel vehicle  |
| ARB               | California Air Resources Board                                    |
| AT-PZEV           | Advanced technology partial zero emission vehicle                 |
| B2B               | battery-to-building   |
| B2G               | battery-to-grid   |
| BYD               | “Build Your Dreams,” a Chinese battery company turned automaker   |
| CAISO             | California Independent System Operator                            |
| CPUC              | California Public Utilities Commission                            |
| DOE               | (U.S.) Department of Energy                                       |
| EDV               | electric-drive vehicle  |
| EISA              | Energy Independence and Security Act of 2007                      |
| EPAct             | Energy Policy Act   |
| EPRI              | Electric Power Research Institute                                 |
| EREV              | extended-range electric vehicle, a series-electric plug-in hybrid |
| ESCO              | energy services company   |
| EV                | (battery) electric vehicle  |
| FCV               | fuel-cell vehicle   |
| FePO <sub>4</sub> | iron-phosphate  |
| gal/y             | gallon per year   |
| GHG               | greenhouse gas  |
| GM                | General Motors  |
| IOU               | investor-owned utility  |
| kW                | kilowatt (power)  |

|                       |   |
|-----------------------|---|
| kWh                   | kilowatt-hour (energy)                                      |
| LDV                   | light-duty vehicle  |
| LiFePO <sub>4</sub>   | lithium-iron-phosphate                                      |
| Li-ion                | lithium-ion   |
| mpg                   | miles per gallon  |
| MW/y                  | Megawatt per year   |
| NiMH                  | nickel-metal hydride  |
| NREL                  | National Renewable Energy Laboratory                        |
| OEM                   | original equipment manufacturer                             |
| PG&E                  | Pacific Gas and Electric                                    |
| PHEV20                | plug-in hybrid electric vehicle with a 20 mile range        |
| PIER                  | Public Interest Energy Research                             |
| PURPA                 | Public Utility Regulatory Policies Act                      |
| R&D                   | research and development                                    |
| RPS                   | renewable portfolio standard                                |
| SCE                   | Southern California Edison                                  |
| TCO <sub>2</sub> /MWh | metric tons of CO <sub>2</sub> equivalent per megawatt-hour |
| UC                    | University of California                                    |
| UK                    | United Kingdom  |
| V2G                   | vehicle-to-grid   |
| ZEV                   | zero-emission vehicle                                       |